รายงานการวิจัย

เทคนิคใหม่ในการออกแบบตัวควบคุมแบบคงทนกำหนดโครงสร้างได้ สำหรับวงจรแปลงผันกระแสตรงเป็นกระแสตรง

A Novel Design Technique for Fixed Structure Robust Control of a DC-DC Converter

ชื่อผู้วิจัย นายสมยศ เกียรติวนิชวิไล

ได้รับทุนสนับสนุนงานวิจัยจากเงินรายได้ ประจำปีงบประมาณ 2551

คณะวิศวกรรมศาสตร์
สถาบันเทคโนโลยีพระจอมเกล้าเจ้าคุณทหารลาดกระบัง

กิตติกรรมประกาศ

นักวิจัยขอขอบคุณคณะวิศวกรรมศาสตร์ สถาบันเทคโนโลยีพระจอมเกล้าเจ้าคุณทหารลาดกระบัง ที่ให้การสนับสนุนทุนวิจัยแก่ทีมวิจัย และขอขอบคุณภาควิชาวิศวกรรมไฟฟ้า คณะวิศวกรรมศาสตร์สถาบันเทคโนโลยีพระจอมเกล้าเจ้าคุณทหารลาดกระบัง ในการสนับสนุนอุปกรณ์ สถานที่ในการดำเนินการวิจัย

ส่วนที่ 1 **รายละเอียดเกี่ยวกับโครงการ**

(ภาษาไทย) เทคนิคใหม่ในการออกแบบตัวควบคุมแบบคงทนกำหนดโครงสร้างได้สำหรับวงจรแปลงผันกระแสตรงเป็นกระแสตรง

(ภาษาอังกฤษ) A Novel Design Technique for Fixed Structure Robust Control of a DC-DC Converter

ได้รับทุนอุดหนุนการวิจัยจาก คณะวิศวกรรมศาสตร์ สถาบันเทคโนโลยีพระจอมเกล้าเจ้าคุณทหารลาดกระบัง ประจำปี 2551 จำนวนเงิน 77,820 บาท

ระยะเวลาทำการวิจัย 1 ปี ตั้งแต่ 2 ต.ค. 2550 ถึง 30 ก.ย. 2551

ส่วนที่ 2 **บทคัดย่อ**

งานวิจัยนี้นำเสนอการออกแบบเทคนิคใหม่ในการออกแบบตัวควบคุมแบบคงทนกำหนดโครงสร้างได้สำหรับวงจรแปลงผันกระแสตรงเป็นกระแสตรง โดยได้นำเสนอเทคนิคการออกแบบใหม่ที่ให้ตัวควบคุมที่ไม่ซับซ้อน มีความคงทนและสมรรถนะดี เทคนิคที่นำเสนอจะออกแบบตัวควบคุมพีไอดีแบบคงทนด้วยเทคนิคขั้นตอนวิธีเชิงพันธุกรรม (Genetic Algorithms) สำหรับวงจรดีซีทูดีซีแบบโหมดกระแส ค่าฟังก์ชันฟิตเนส (Fitness Function)ในขั้นตอนวิธีเชิงพันธุกรรมใช้ค่าส่วนกลับของนอร์มอนันต์ของฟังก์ชันถ่ายโอนจากตัวรบกวนไปยังเอาต์พุต หลักการนี้ซึ่งเป็นส่วนหนึ่งของเทคนิคการจัดสัณฐานวงรอบเอชอินฟินิตี้ (H infinity) เพื่อให้ตัวควบคุมที่ออกแบบมีสมรรถนะและความคงทนสูง จากผลงานวิจัยแสดงให้เห็นถึงความสามารถในการนำไปประยุกต์ใช้งานของตัวควบคุมตามแนวคิดที่ออกแบบขึ้น นอกจากนี้ในรายงานฉบับนี้ยังได้แสดงการประยุกต์เทคนิคที่นำเสนอกับระบบอื่นๆ อาทิเช่น ระบบเครื่องบิน HIMAT และระบบทางไฟฟ้ากำลัง เพื่อให้เห็นแนวทางการพัฒนาต่อในงานวิจัยที่นำเสนอนี้

This research proposes a novel fixed-structure robust controller design for DC/DC converter. The proposed technique can design a simple structure, robust and high performance controller. In the proposed technique, Robust PID controller for current mode DC/DC converter is designed by Genetic Algorithms. Inverse of infinity norm from disturbances to states is formulated as fitness function in GA. This concept is based on particular concept of H infinity loop shaping that makes the controller high robust performance. As seen in the results, the practical use of the proposed technique has been clearly shown. In addition, the application of the proposed technique in other systems such as HIMAT system, power system, etc. were shown in the report to illustrate the future work of this research.

สารบัญ

สารบัญตาราง

สารบัญภาพ

1. บทนำ

1.1 บทนำ

งานวิจัยนี้นำเสนอการออกแบบเทคนิคใหม่ในการออกแบบตัวควบคุมแบบคงทนกำหนดโครงสร้างได้สำหรับวงจรแปลงผันกระแสตรงเป็นกระแสตรง โดยได้นำเสนอเทคนิคการออกแบบใหม่ที่ให้ตัวควบคุมที่ไม่ซับซ้อน มีความคงทนและสมรรถนะดี เพื่อแก้ปัญหาตัวควบคุมแบบคงทนบบเดิมที่ซับซ้อน โดยเทคนิคที่นำเสนอจะออกแบบตัวควบคุมพีไอดีแบบคงทนด้วยเทคนิคขั้นตอนวิธีเชิงพันธุกรรม (Genetic Algorithms) สำหรับวงจรดีซีทูดีซีแบบโหมดกระแส เทคนิคที่ใช้ในการออกแบบจะกำหนดโครงสร้างของตัวควบคุมเป็นแบบพีไอดีก่อน จากนั้นจึงใช้วิธีขั้นตอนเชิงพันธุกรรมในการหาค่าพารามิเตอร์ของตัวควบคุม ค่าฟังก์ชันฟิตเนส (Fitness Function) ในขั้นตอนวิธีเชิงพันธุกรรม ใช้ค่าส่วนกลับของนอร์มอนันต์ของฟังก์ชันถ่ายโอนจากตัวรบกวนไปยังเอาต์พุตซึ่งเป็นส่วนหนึ่งของเทคนิคการจัดสัณฐานวงรอบเอชอินฟินิตี้ (H infinity) เพื่อให้ตัวควบคุมที่ออกแบบมีสมรรถนะและความคงทนสูง จากผลงานวิจัยแสดงให้เห็นถึงความสามารถในการนำไปประยุกต์ใช้งานของตัวควบคุมตามแนวคิดที่ออกแบบขึ้น ในงานวิจัยนี้ยังได้ประยุกต์ใช้กับระบบ MPPT ในแผงโซล่าร์เซลล์เพื่อให้เห็นการประยุกต์ใช้งานของวงจรนอกจากนี้ในตอนท้ายของรายงานได้แสดงการประยุกต์เทคนิคที่นำเสนอกับระบบอื่นๆ

2. เอาท์พุทที่ได้จากโครงการในรอบ 1 ปี

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ง.ต้นแบบวงจร จำนวน 1 ต้นแบบ

3.ทฤษฎีและระบบที่ทดลอง

วงจรที่สำคัญวงจรหนึ่งในการออกแบบทางอิเล็กทรอนิกส์กำลัง คือ วงจรแปลงกระแสตรงเป็นกระแสตรง วงจรเหล่านี้ใช้ในอุปกรณ์หลายชนิด อาทิเช่น ระบบอัดประจุไฟฟ้า วงจรขับกระแสตรง (DC Drive) และวงจรหาจุดที่มีกำลังทางไฟฟ้าสูงสุดของแผงโซล่าเซลล์ (Maximum Power Point Tracking) เป็นต้น ในการควบคุมวงจรนี้ให้เป็นระบบที่มีสมรรถนะสูง มีความคงทนต่อสภาวะแวดล้อมที่เปลี่ยนไปนับว่ามีความสำคัญอย่างยิ่ง อย่างไรก็ตามการออกแบบตัวควบคุมแบบคงทนมักส่งผลให้ตัวควบคุมมีความซับซ้อนลำดับสูงและยากต่อการนำไปใช้งานจริง เพื่อแก้ปัญหาดังกล่าวงานวิจัยนี้จึงนำเสนอการควบคุมแบบคงทน(Robust Control)โดยอาศัยเทคนิคการจัดสัณฐานวงรอบเอชอินฟินิตี้ (H Infinity Loop Shaping) และใช้ขั้นตอนวิธีเชิงพันธุกรรมในการออกแบบทำให้ตัวควบคุมสามารถกำหนดโครงสร้างได้ มีความคงทนและโครงสร้างไม่ซับซ้อนซึ่งเหมาะสำหรับการนำไปใช้งานจริง ในหัวข้อนี้จะกล่าวถึงพื้นฐานในเรื่องการควบคุมแบบคงทน การจัดสัณฐานวงรอบเอชอินฟินิตี้และการออกแบบเทคนิคที่นำเสนอในโครงงานวิจัยนี้ คือ การออกแบบระบบควบคุมแบบคงทนแบบกำหนดโครงสร้างได้ด้วยวิธีขั้นตอนเชิงพันธุกรรม

3.1 ตัวควบคุมแบบคงทนและการจัดสัณฐานวงรอบเอชอินฟินิตี้

เทคนิคในระบบควบคุมแบบคงทนโดยทั่วไปจะมีความแตกต่างในการออกแบบขึ้นกับแบบจำลองทางคณิตศาสตร์ (Mathematical Model) ที่นำมาใช้กำหนดโมเดลของความไม่แน่นอน ซึ่งในความจริงแล้วความไม่แน่นอนของระบบอาจเกิดขึ้นได้เนื่องจาก สภาวะแวดล้อมหรือพารามิเตอร์ของระบบเปลี่ยนไป การเกิดตัวก่อกวน ดังนั้นระบบควบคุมที่ดีจะต้องคำนึงถึงสภาพที่ไม่แน่นอนเหล่านี้ในการออกแบบด้วย แบบจำลองที่มีสภาวะความไม่แน่นอนของแบบจำลองอยู่ เรียกว่า แบบจำลองความไม่แน่นอน (Uncertainty Models) สมการข้างล่างนี้แสดงให้เห็นถึงความแตกต่างระหว่างแบบจำลองที่คำนึงและไม่คำนึงถึงความไม่นอนของระบบโดยทั่วไป

แบบจำลองทางคณิตศาสตร์ (G_o) ที่ไม่คำนึงถึงความไม่แน่นอน

Mathematical Model $\longleftrightarrow$ G_o

ระบบจริง (G_Δ) ที่คำนึงถึงความไม่แน่นอน (ตัวอย่าง)

Real Process $\longleftrightarrow$ $G_\Delta = G_o + \Delta G$

เมื่อ

Δ คือ แบบจำลองโมเดลความไม่แน่นอนและ G_o คือ ฟังก์ชันถ่ายโอนของนอมินอลแพนท์ (nominal plant) ตัวแทนของระบบ แบบจำลองความไม่แน่นอนสามารถจำลองได้ในหลายรูปแบบ ดังตารางข้างล่างนี้

ตารางที่ 3.1 แสดงชนิดของแบบจำลองความไม่แน่นอน (Uncertainty Models) [1]

แบบจำลอง	ลักษณะของความไม่แน่นอนที่เกิดขึ้น
1.Additive uncertainty model $G_\Delta = G_0 + \Delta$	ความไม่แน่นอนที่เกิดจากซีโร่ (zeros)
2.Multiplicative uncertainty model $G_\Delta = (I + \Delta)\, G_0$	ความไม่แน่นอนที่เกิดจากซีโร่ (zeros)
3.Feedback uncertainty model $G_\Delta = G_0(I + \Delta G_0)^{-1}$	ความไม่แน่นอนที่เกิดจากโพล (poles)
4.Coprime factor uncertainty model $G_\Delta = (N + \Delta_N)\,(M + \Delta_M)^{-1}$	ความไม่แน่นอนที่เกิดจากซีโร่ (zeros) และโพล (poles)

ในงานวิจัยนี้เลือกใช้แบบจำลองเป็นแบบ Co-prime factor เนื่องจากสามารถรองรับความไม่แน่นอนที่เกิดขึ้นกับโพล (poles) และซีโร่ (zeros) เมื่อพิจารณาระบบ G เป็นแบบ Co-prime factor จะได้ $G = M^{1}N$ จากรูปที่ 3.1 ถ้าระบบ G_p ประกอบไปด้วยฟังก์ชันถ่ายโอนที่มีความไม่แน่นอนคือ Δ_M, Δ_N จะได้

$$G_p = \{(M+\Delta_M)^{-1}(N+\Delta_N) \;:\; \left\|[\Delta_N \quad \Delta_M]\right\|_\infty < \varepsilon\} \;\Rightarrow\; \begin{bmatrix} A & B \\ C & D \end{bmatrix} \qquad (3.1)$$

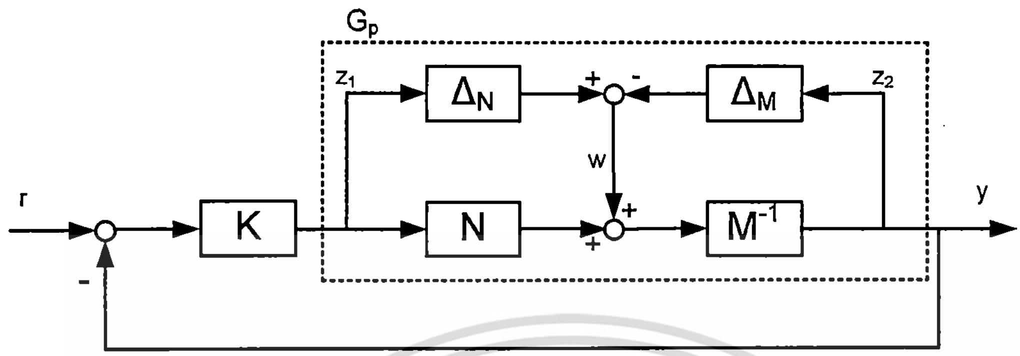
เมื่อ

ε คือ ส่วนเผื่อเสถียรภาพ และ

A , B , C , D คือ ปริภูมิสถานะ (state – space) ของระบบ G_p

ระบบจะมีเสถียรภาพก็ต่อเมื่อนอร์มอนันต์ของ Δ_M , Δ_N มีค่าน้อยกว่าส่วนเผื่อเสถียรภาพ [2] โดยที่นอร์มอนันต์ ($\|\;\|_\infty$) คือ ค่าอัตราการขยายสูงที่สุดของฟังก์ชันถ่ายโอน Δ_M , Δ_N

รูปที่ 3.1 แสดงแผนภาพอธิบายความไม่แน่นอนแบบ co-prime ซึ่งจะเห็นได้ว่าความไม่แน่นอนจะเกิดขึ้นในลักษณะของส่วนตัวตั้งและตัวหารของระบบ



รูปที่ 3.1 แสดงภาพ Uncertainty Co-prime factor

เมื่อพิจารณาระบบควบคุมแบบป้อนกลับที่มีตัวรบกวน ระบบจะมีความคงทนถ้าระบบควบคุมแบบป้อนกลับ G มีเสถียรภาพและ

$$\left\| T_{zw} \right\|_{\infty} = \left\| \begin{bmatrix} I \\ K \end{bmatrix} (I + G_p K)^{-1} M^{-1} \right\|_{\infty} \le \frac{1}{\varepsilon} \tag{3.2}$$

เมื่อ $\|T_{zw}\|_{\infty}$ คือ ค่านอร์มอนันต์ (Infinity norm) ของฟังก์ชันถ่ายโอนจากตัวรบกวน (disturbance) ไปยังสเตท โดยที่ส่วนเผื่อเสถียรภาพสูงสุด (ε_{max}) จะสามารถหาได้จากการแก้สมการริคาติ (Riccati Equation) ต่อไปนี้

$$\frac{1}{\varepsilon_{max}} = (1 + \lambda_{max}(XZ))^{\frac{1}{2}} \tag{3.3}$$

เมื่อ λ_{max}(XZ) คือ ค่า Eigen values ของเมตริกซ์ X คูณกับเมตริกซ์ Z โดยที่ Z คือ ค่าที่ได้จากการแก้สมการริคาติ [2]ต่อไปนี้

$$(A - BS^{-1}D^{T}C)Z + Z(A - BS^{-1}D^{T}C)^{T} - ZC^{T}R^{-1}CZ + BS^{-1}B^{T} = 0 \tag{3.4}$$

และ X คือ ค่าที่ได้จากการแก้สมการริคาติต่อไปนี้

$$(A - BS^{-1}D^{T}C)^{T} X + X(A - BS^{-1}D^{T}C) - XBS^{-1}B^{T}X + C^{T}R^{-1}C = 0 \tag{3.5}$$

โดยที่ $R = I + DD^T \quad , \quad S = I + D^T D$

จากนั้นเลือกค่าเผื่อเสถียรภาพให้มีค่าต่ำกว่าค่าส่วนเผื่อเสถียรภาพสูงสุดเล็กน้อย ($\varepsilon < \varepsilon_{max}$) [2] เพื่อสังเคราะห์หาชุดควบคุม K จากสมการต่อไปนี้ [2]

$$K_\infty = \left[\begin{array}{c|c} A+BF+\gamma^2(L^T)^{-1}ZC^T(C+DF) & \gamma^2(L^T)^{-1}ZC^T \\ \hline B^T X & -D^T \end{array}\right] \tag{3.6}$$

เมื่อ $S = I + D^T D \quad F = -S^{-1}(D^T C + B^T X) \quad \gamma = \dfrac{1}{\varepsilon} \quad L = (1-\gamma^2)I + XZ$

อย่างไรก็ตาม การออกแบบด้วยวิธีการข้างต้นจะได้ระบบที่มีความคงทนแต่ยังไม่ได้คำนึงถึงสมรรถนะ วิธีการหนึ่งที่สามารถคำนึงถึงความคงทนและสมรรถนะได้ในการออกแบบนำเสนอโดย [3] คือ

การออกแบบตัวควบคุมแบบจัดสัณฐานวงรอบเอชอินฟินิตี้ ซึ่งมีขั้นตอนในการออกแบบดังนี้ [3]

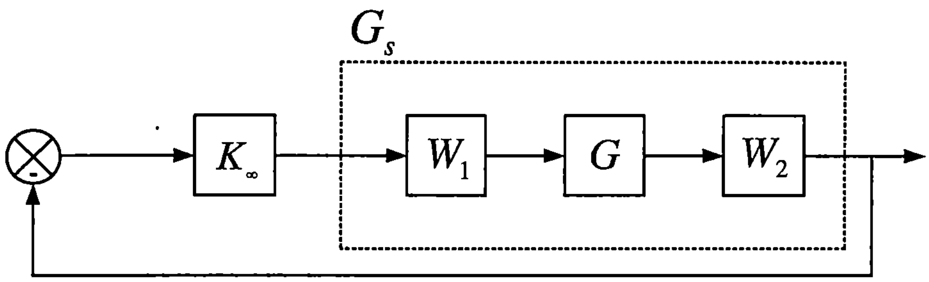
1. ทำการจัดสัณฐานวงรอบของระบบ G โดยใช้ฟังก์ชันน้ำหนักชดเชยก่อน (pre-compensation) คือ W_1 และมีฟังก์ชันน้ำหนักชดเชยหลัง (post-compensation) คือ W_2 ซึ่งฟังก์ชัน W_2 อาจพิจารณาตัดทิ้งได้หากสมมติว่าสัญญาณรบกวนที่มาจากตัวตรวจจับสัญญาณมีค่าน้อย โดยกำหนดให้ค่า W_2 เป็นค่าคงที่ โดยทั่วไปมักกำหนดค่า ฟังก์ชั่นน้ำหนักตามหลักการจัดสัณฐานวงรอบ ซึ่งอาจใช้ตามสมการต่อไปนี้

$$W_1 = K_w \frac{s+\alpha}{s+\delta}, \qquad W_2 = I \tag{3.7}$$

โดยกำหนดให้ K_w , α และ δ ที่มีค่าบวก และค่า δ เป็นค่าบวกที่มีค่าน้อยมาก เพื่อให้เกิดในลักษณะฟังก์ชั่นอินทิเกรตในระบบที่จัดสัณฐาน ทำให้ไม่มีค่าความผิดพลาดในสภาวะคงตัว (steady state error) จากการจัดสัณฐานข้างต้นจะได้ระบบที่จัดสัณฐานแล้วเป็น

$$G_s = W_1 G W_2 \tag{3.8}$$

เมื่อ G_s คือ ระบบที่มีการจัดสัณฐานวงรอบแล้ว



รูปที่ 3.2 แสดงภาพการจัดสัณฐานวงรอบเอชอินฟินิตี้

2. หาค่านอร์มอนันต์ที่ต่ำที่สุดที่จะเกิดตัวตัวควบคุม K โดยค่านี้เรียกว่า γ_{min}

$$\frac{1}{\varepsilon_{max}} = (1+\lambda_{max}(XZ))^{\frac{1}{2}} \tag{3.9}$$

ตามข้อแนะนำใน [1] ถ้า $\varepsilon_{max} < 0.25$ แสดงว่า W_1 และ W_2 ที่ออกแบบไว้ไม่เหมาะสมต้องทำการออกแบบในขั้นตอนที่ 1 ใหม่

3.เลือกค่า $\varepsilon < \varepsilon_{max}$ และสังเคราะห์หาชุดควบคุม K∞

$$\left\|T_{zw}\right\|_\infty = \left\|\begin{bmatrix} I \\ K_\infty \end{bmatrix}(I+G_sK_\infty)^{-1}M_s^{-1}\right\|_\infty \le \varepsilon^{-1} \tag{3.10}$$

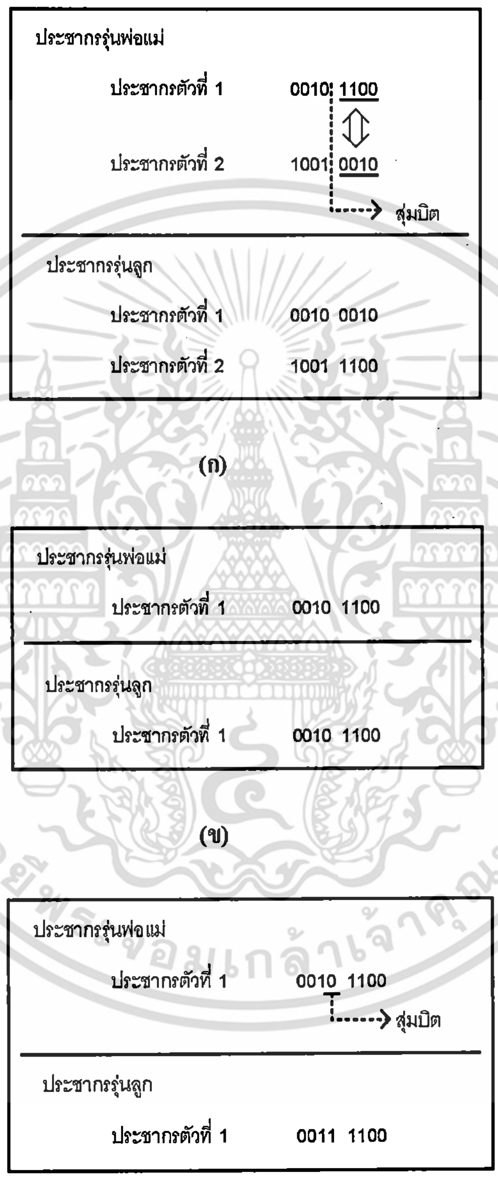
4.จะได้ตัวควบคุม K ที่นำไปใช้งาน จาก

$$K = W_1K_\infty K_2 \tag{3.11}$$

3.2 วิธีการขั้นตอนเชิงพันธุกรรม

ขั้นตอนวิธีเชิงพันธุกรรมเป็นส่วนหนึ่งของการหาค่าที่เหมาะสม (Optimization) ซึ่งสามารถนำไปใช้ในการแก้ปัญหาที่ไม่เป็นเชิงเส้น (nonlinear)ได้ ขั้นตอนวิธีเชิงพันธุกรรมนี้จะเป็นการพิจารณาแก้ปัญหาโดยแบ่งระดับหน่วยย่อยที่สุดเป็นโครโมโซม ในแต่ละรุ่น (Generation)จะมีโครโมโซมรวมกันอยู่และจะเรียกโครโมโซมเหล่านี้ว่าประชากร (Population) ประชากรแต่ละตัวในรุ่นจะมีค่าฟิตเนส (Fitness) แตกต่างกันไป ในงานวิจัยนี้จะกำหนดให้ค่าพารามิเตอร์ p ของตัวควบคุม $K(p)$ คือประชากรและประชากรแต่ละตัวจะสามารถหาค่าฟังก์ชันฟิตเนสได้จากการแทนค่าพารามิเตอร์ p ในสมการ (3.10) เพื่อหาค่า J_{cost} ออกมา โดยที่ส่วนกลับของ J_{cost} คือค่าฟิตเนส (Fitness)

$$Fitness = \frac{1}{J_{cost}} \tag{3.12}$$



(ค)

รูปที่ 3.3 (ก) แบบที่ผสมข้ามพันธุ์ , (ข) แบบที่ถอดแบบจากต้นแบบ และ (ค) แบบที่กลายพันธุ์ [4]

จากขั้นตอนวิธีเชิงพันธุกรรมจะเริ่มจากการสุ่มประชากรหรือค่าพารามิเตอร์ p โดยที่พารามิเตอร์ p ตัวใดที่ทำให้ค่าฟิตเนสมีค่าสูงที่สุดจะถูกเลือกมาเป็นคำตอบในรุ่นแรก (Generation = 1) จากนั้นก็เริ่มหาประชากรรุ่นถัดไปโดย*การดำเนินการทางพันธุกรรม* ซึ่งเป็นการถ่ายทอดพันธุกรรมจากประชากรรุ่นพ่อแม่ไปสู่ประชากรรุ่นลูก (generation = 2) ต่อไป โดยการดำเนินการทางพันธุกรรมจะแบ่งออกเป็น 3 แบบดังนี้

- แบบที่ผสมข้ามพันธุ์ (Cross-Over)

- แบบที่ถอดแบบจากต้นแบบ (Reproduction)

- แบบที่กลายพันธุ์ (Mutation)

รายละเอียดของขั้นตอนวิธีเชิงพันธุกรรมสามารถดูได้จาก รูปที่ 3.3 และรายละเอียดของ GA สามารถดูได้จาก [4]

3.3 วิธีการออกแบบตัวควบคุมแบบกำหนดโครงสร้างได้ด้วยวิธีขั้นตอนเชิงพันธุกรรม

ตัวควบคุมที่ออกแบบโดยวิธีเอชอินฟินิตี้ในหัวข้อที่ 3.1 นั้น แม้ว่าจะมีสมรรถนะที่ดีและความคงทนสูง แต่โดยมากมักจะมีโครงสร้างที่ซับซ้อน ลำดับสูงและยากต่อการนำไปใช้งาน การออกแบบตัวควบคุมที่กำหนดโครงสร้างได้ด้วยขั้นตอนวิธีเชิงพันธุกรรม จะกำหนดโครงสร้างของตัวควบคุมเป็น $K(p)$ ก่อนแล้วหาพารามิเตอร์ในตัวควบคุมนี้ให้สอดคล้องกับระบบซึ่งในโครงงานวิจัยนี้ จะกำหนดโครงสร้างตัวควบคุมให้เป็นแบบพีไอดี

$$K(p) = K_p + \frac{K_i}{s} + K_d s \qquad (3.13)$$

เมื่อ p คือ เวกเตอร์พารามิเตอร์ของตัวควบคุมที่ต้องการหา สามารถเขียนได้ดังนี้ $p = [Kp, Ki, Kd]$ ในงานวิจัยนี้จะใช้ขั้นตอนวิธีเชิงพันธุกรรมหาค่าพารามิเตอร์ p ที่เหมาะสมที่สุด จากหลักการในหัวข้อ 3.1 ค่าพารามิเตอร์ p ที่เหมาะสมจะทำให้ระบบควบคุมมีค่านอร์มอนันต์ (Infinity norm) ของฟังก์ชันถ่ายโอนจากตัวรบกวน (disturbance) ไปยังสเตท ($\|T_{zw}\|_\infty$) มีค่าต่ำที่สุดและจากสมการที่ 3.11 จะหาชุดควบคุมได้จาก

$$K(p) = W_1 K_\infty W_2 \qquad (3.14)$$

$$K_\infty W_2 = \frac{K(p)}{W_1} \qquad (3.15)$$

โดยกำหนดให้ $W_1^{-1} \in \Re H_\infty$ และให้ $W_2 = I$ คือค่าคงที่เพราะจะไม่นำเรื่องการชดเชยเรื่องสัญญาณรบกวนของตัวตรวจจับสัญญาณมาคิด

$$K_\infty = \frac{K(p)}{W_1} \tag{3.16}$$

นำค่า K_∞ แทนค่าในสมการที่ (3.10) โดยกำหนดให้ $\|T_{zw}\|_\infty$ เป็นฟังก์ชัน $J_{\cos t}$ ซึ่งจะต้องหาค่าพารามิเตอร์ p ที่ทำให้ได้ค่า $J_{\cos t}$ ในสมการที่ 3.10 มีค่าต่ำที่สุด

$$J_{cost} = \|T_{zw}\|_\infty = \left\| \begin{bmatrix} I \\ W_1^{-1}K(p) \end{bmatrix} (I + G_s W_1^{-1} K(p))^{-1} M_s^{-1} \right\|_\infty \tag{3.17}$$

การหาค่า p ที่เหมาะสมที่สุดด้วยวิธีขั้นตอนเชิงพันธุกรรม

รูปที่ 3.4 แสดงขั้นตอนทั้งหมดของวิธีการที่นำเสนอในงานวิจัยนี้ โดยสามารถสรุปขั้นตอนการดำเนินงานของงานวิจัยได้ดังนี้ ขั้นตอนแรกจะต้องมีการออกแบบค่าฟังก์ชันน้ำหนักชดเชยก่อน (W_1) และหลัง (W_2) จะต้องออกแบบให้มีค่า $\varepsilon_{max} > 0.25$ การออกแบบด้วยวิธีเชิงพันธุกรรมจะสุ่มประชากรหรือค่าพารามิเตอร์ p โดยพารามิเตอร์นี้จะมีทั้งแบบที่ถอดแบบมาจากต้นแบบ (Reproduction) แบบที่ผสมข้ามพันธุ์ (Crossover) และแบบที่กลายพันธุ์ (Mutation) โดยที่พารามิเตอร์ p ตัวที่ทำให้ค่าฟิตเนสมีค่าสูงที่สุดจะถูกเลือกมาเป็นคำตอบในรุ่นแรก (Generation = 1) ต่อไปจะเริ่มทำในรุ่นต่อไป (Generation = 2,3,4,…) เพื่อหาค่าพารามิเตอร์ p ในรุ่นถัดไปเรื่อยๆ จนถึงลำดับรุ่นที่เราต้องการ สรุปขั้นตอนวิธีการที่นำเสนอได้ดังนี้

ขั้นตอนที่ 1 และ **2** เหมือนกับขั้นตอนของ McFarlane และ Glover ในหัวข้อที่ 3.1 หากค่า $\varepsilon_{opt} < 0.25$ (หรือ $\gamma_{opt} > 4$) หมายความว่าฟังก์ชันน้ำหนัก W_1 และ W_2 ที่ออกแบบไว้ไม่เหมาะสมให้ทำการปรับฟังก์ชันเหล่านี้ใหม่

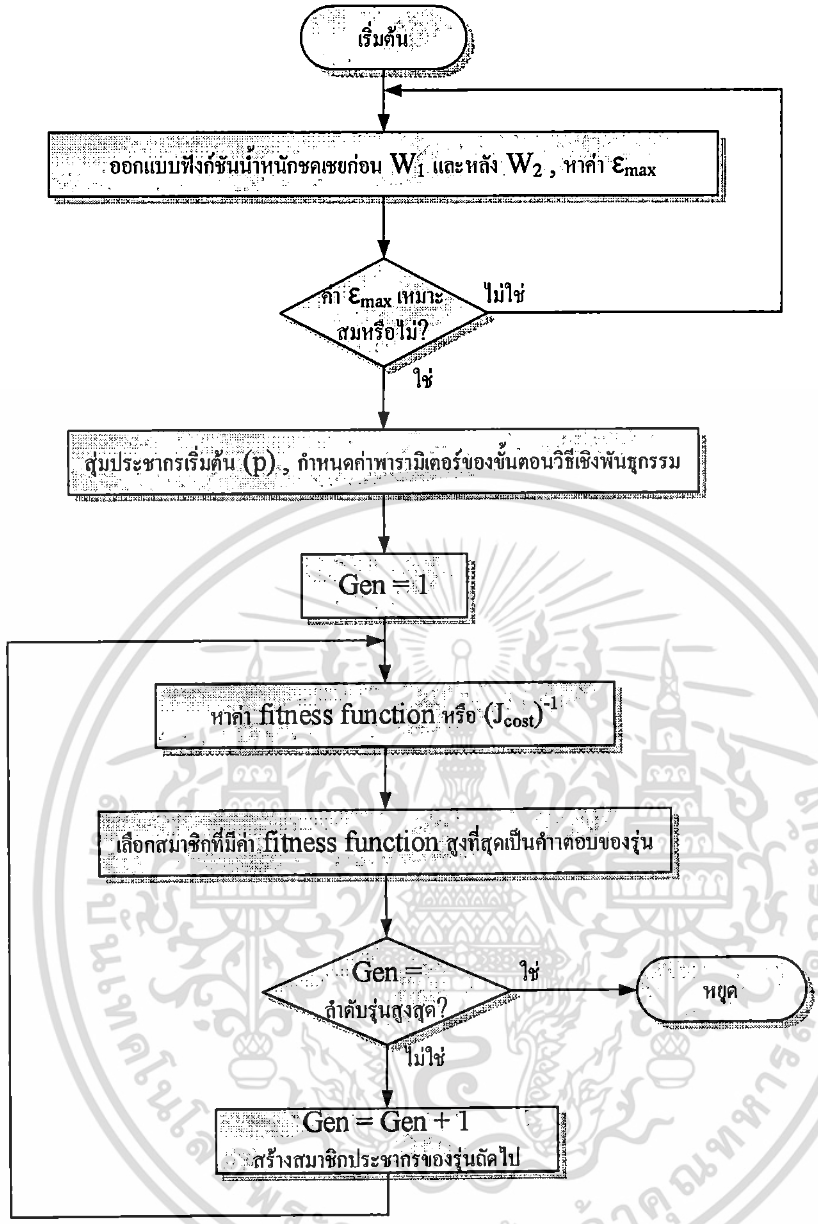
ขั้นตอนที่ 3 กำหนดโครงสร้างของชุดควบคุม *K(p)* และทำการสุ่มค่าเริ่มต้นของประชากร p ในรุ่น (Generation) ที่ 1 กำหนดค่าพารามิเตอร์ของการคำนวณต่างๆ ของขั้นตอนวิธีเชิงพันธุกรรม เช่น ขนาดของจำนวนประชากร ค่าความน่าจะเป็นของการผสมข้ามพันธุ์ (cross over) การกลายพันธุ์ (mutation) ลำดับรุ่นสูงสุด(maximum generation)

ขั้นตอนที่ 4 คำนวณค่าฟังก์ชัน J_{cost} ของแต่ละสมาชิกในประชากรรุ่นนี้โดยใช้สมการที่ (3.17) กำหนดให้ $J_{cost} = 100$ หรือค่าจำนวนมากๆ หาก *K(p)* ที่ได้จากสมาชิกนั้นไม่ทำให้ระบบมีเสถียรภาพ เลือกสมาชิกในประชากรที่ให้ค่า J_{cost} ต่ำที่สุดเป็นคำตอบของรุ่นปัจจุบัน สำหรับรุ่นแรก (Gen = 1)

ขั้นตอนที่ 5 ไปรุ่นถัดไป Gen=Gen+1

ขั้นตอนที่ 6 หากรุ่นปัจจุบันไม่ใช่ลำดับรุ่นสูงสุดที่กำหนดไว้ ให้สร้างสมาชิกของประชากรใหม่จากวิธีทางพันธุกรรม แล้วเริ่มขั้นตอนที่ 4 ใหม่อีกครั้งจนกระทั่งถึงลำดับรุ่นสูงสุด

ขั้นตอนที่ 7 ตรวจสอบสมรรถนะของระบบทั้งในโดเมนความถี่และโดเมนเวลา ถ้าสมรรถนะระบบยังไม่เหมาะสมให้เริ่มต้นขั้นตอนที่ 1 ใหม่อีกครั้งโดยปรับค่าฟังก์ชันน้ำหนักหรือเปลี่ยนโครงสร้างของตัวควบคุม รูปที่ 3.4 แสดงถึงแผนผังการทำงานของขั้นตอนวิธีที่นำเสนอนี้



รูปที่ 3.4 แสดงแผนผังการทำงานของการออกแบบขั้นตอนวิธีเชิงพันธุกรรม

4. การทดลองและผลการทดลอง

ระบบที่ทำการทดสอบในรายงานฉบับนี้ เป็นดีซีทูดีซีคอมเวอร์เตอร์ สองระบบเพื่อยืนยันความสามารถของเทคนิคที่นำเสนอ ระบบแรกเป็น ระบบควบคุมแบบ ACMC Buck Converter และระบบที่สองเป็น PCMC Buck-Boost Converter ในตอนท้ายของบทนี้จะแสดงรายละเอียดของการนำไปประยุกต์ใช้ในระบบ MIMO System บางระบบด้วย

4.1 ระบบควบคุมสำหรับวงจร Buck Converter แบบ ACMC Mode

วงจรทอนระดับแรงดัน (Buck Converter) ที่เป็นแบบโหมดกระแสเฉลี่ย (Average Current Mode) จะมีอินพุตที่ป้อนเข้าไปในระบบคือ สัญญาณควบคุม (Control Reference) และมีเอาต์พุตคือแรงดันเอาต์พุต (Output Voltage) โดยประกอบด้วยสองวงรอบคือ วงรอบกระแสและวงรอบแรงดัน เมื่อออกแบบวงรอบกระแสอย่างเหมาะสมแล้ว จะมีฟังก์ชันถ่ายโอนของวงจรทอนระดับแรงดันแบบโหมดกระแสเฉลี่ยจากกระแสอ้างอิง $V_c(s)$ ไปยังแรงดันเอาต์พุต $V_o(s)$ ดังนี้

$$\frac{V_o(s)}{V_c(s)} = \frac{K_m(1 + r_c Cs)[G_{CA} + 1]G_{dv}(s)}{1 + T_c(s)} \tag{4.1}$$

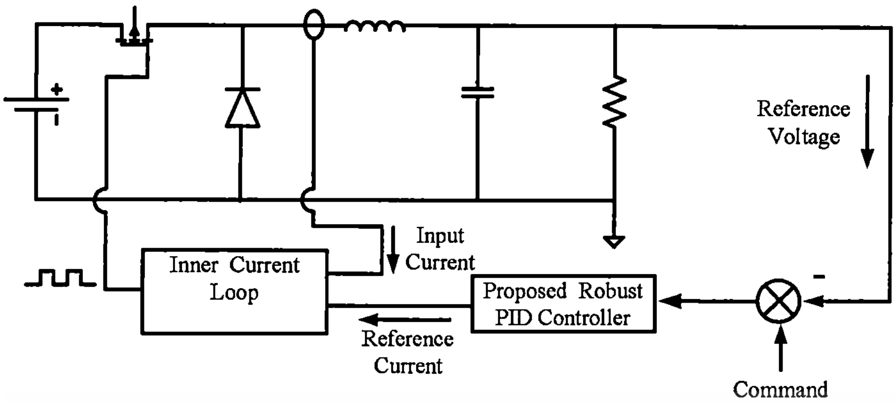
เมื่อ

$$K_m = \frac{1}{V_m}$$

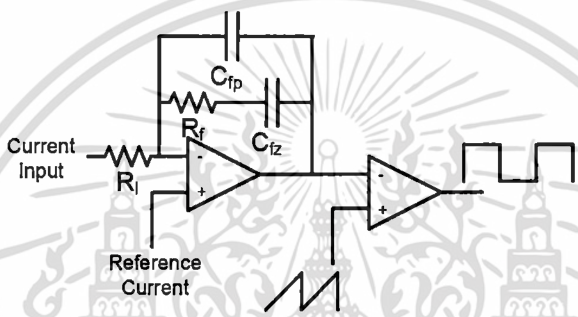
$$T_c(s) = \frac{R_S K_m V_g [1 + (R + r_C)Cs][1 + G_{CA}]}{R + (L + RCr_C)s + (RLC + r_C LC)s^2}$$

$$G_{dv}(s) = \frac{(1 + r_C Cs)V_g}{R + (L + RCr_C)s + (RLC + r_C LC)s^2}$$

ค่า R, L, C และ r_C คือ ค่าความต้านทานของโหลด ค่าความเหนี่ยวนำ ค่าความจุของตัวเก็บประจุ และค่าความต้านทานแฝงของตัวเก็บประจุ ตามลำดับ ส่วนค่า G_{CA} สามารถดูได้จากการออกแบบวงรอบควบคุมกระแสภายใน



รูปที่ 4.1 แสดงภาพวงจรทอนระดับแรงดันแบบโหมดกระแส



รูปที่ 4.2 แสดงภาพชุดควบคุมกระแสวงรอบใน (Inner Current Loop)

4.1.1 การออกแบบวงรอบควบคุมกระแสภายใน (Inner Current-Loop)

การออกแบบวงรอบควบคุมกระแสภายใน (Inner Current-Loop) แบบควบคุมกระแสเฉลี่ย (Average Current – Mode) จะเป็นวงรอบที่มีการควบคุมแบบ PI-Control ซึ่งสามารถออกแบบค่าอัตราการขยายของวงรอบใน (Gain of Current-Loop) ได้ตาม [5]

$$G_{CA} = \frac{K_c(1+\frac{s}{\omega_z})}{s(1+\frac{s}{\omega_p})} \tag{4.2}$$

เมื่อ

$$K_c = \frac{1}{R_I(C_{fp}+C_{fz})}$$

$$\omega_z = \frac{1}{R_f C_{fz}}$$

$$\omega_p = \frac{C_{fz}+C_{fp}}{R_f C_{fz} C_{fp}}$$

ค่าอัตราการขยายของวงรอบในสามารถออกแบบให้มีขนาดเท่ากับอัตราส่วนของ (R_f / R_l) และอัตราส่วนของ (R_f / R_l) สามารถประมาณค่าได้จากความสัมพันธ์ดังนี้

$$G_{CA} \cong \frac{R_f}{R_l} < \min\{\frac{2V_m f_s L}{V_g R_s}, \frac{V_m f_s L}{V_0 R_s}\} \quad (4.3)$$

เมื่อ

V_m คือ ค่าจากยอดถึงยอดของสัญญาณรูปสามเหลี่ยม (Ramp)

R_s คือ ค่าความต้านทานของตัวต้านทานตรวจจับกระแส

V_g คือ แรงดันทางด้านอินพุต

L คือ ค่าความเหนี่ยวนำของวงจรทบระดับแรงดัน

R_f , R_l คือ ค่าพารามิเตอร์ต่างๆ ดังที่แสดงในรูปที่ 2.5

สมการ (4.3) สามารถนำมาใช้ในการเลือกค่าความต้านทาน R_f และ R_l แล้วกำหนดค่า ω_z ให้มีค่าเท่ากับครึ่งหนึ่งของ ω_0 เมื่อ $\omega_0 = \frac{1}{\sqrt{LC}}$ และค่า ω_p มีค่าเท่ากับครึ่งหนึ่งของความถี่สวิตซิ่ง โดยในงานวิจัยนี้ กำหนดพารามิเตอร์ของวงจรทอนระดับแรงดันต่างๆ ดังนี้

Table 1 Chosen converter's parameter and considered variation ranges

Parameter	**Name**	**Nominal Value**
R_L	Load Resistant	1.5 Ω
V_o	Output Voltage	10 V
V_i	Input Voltage	24 V
L	Inductance	100 μH
C	Capacitor	680 μF
f_{sw}	Switching frequency	100 kHz

จากนั้นสามารถออกแบบหาค่าพารามิเตอร์ของตัวควบคุมวงรอบกระแสภายในได้ดังนี้ R_f = 10kΩ , R_l = 1kΩ , C_{fp} = 2nF , C_{fz} = 50nF

4.1.1 การออกแบบวงรอบควบคุมกระแสนอก แรงดัน (Outer Voltage Loop)

เมื่อแทนค่าพารามิเตอร์ต่างๆ ของวงจรทอนระดับแรงดัน จะได้ฟังก์ชันถ่ายโอนของวงจรทอนระดับแรงดันแบบโหมดกระแสเฉลี่ย จากกระแสอ้างอิง (Current Reference) ไปยังแรงดันทางด้านเอาต์พุต (Output Voltage) ดังสมการที่ (4.4)

$$\frac{V_o(s)}{V_c(s)} = G = \frac{9.79\times10^{-17}s^5 + 5.69\times10^{-11}s^4 + 2.74\times10^{-6}s^3 + 0.007s^2 + 43.97s + 6.63\times10^4}{4.16\times10^{-24}s^7 + 4.74\times10^{-19}s^6 + 4.04\times10^{-14}s^5 + 1.46\times10^{-9}s^4 + 5.77\times10^{-6}s^3 + 0.02s^2 + 58.09s + 3.31\times10^4} \quad (4.4)$$

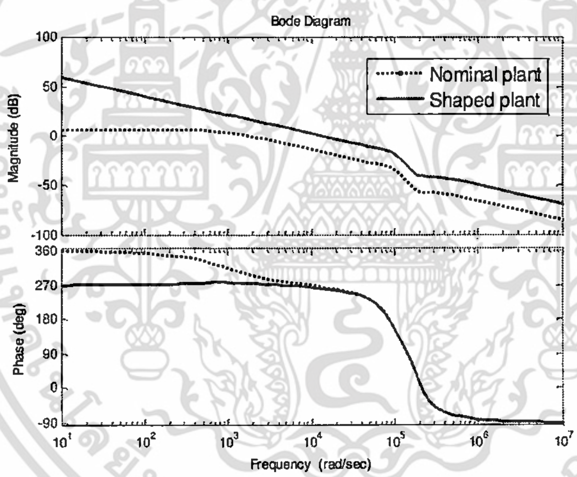
ซึ่งสามารถลดรูปด้วยเทคนิค Hankel Norm Model Reduction ได้เป็น

$$\frac{V_o(s)}{V_c(s)} = G = \frac{514.8s^2 - 4.72\times10^7 s + 1.79\times10^{13}}{s^3 + 7.71\times10^4 s^2 + 9.29\times10^9 s + 9.12\times10^{12}} \quad (4.5)$$

เลือก Weight W1 เป็น

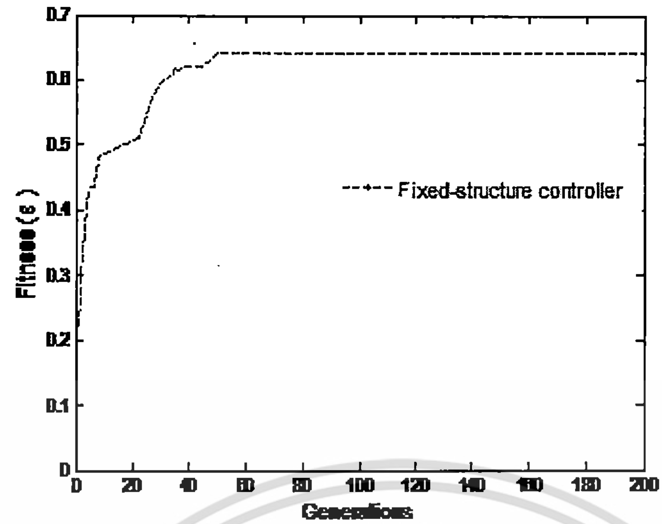
$$W_1(x) = \frac{4.17s + 3425.8}{s + 0.001}$$

ด้วย Weight นี้จะทำให้ระบบมีค่า แบนด์วิดท์เพิ่มจาก 1000 rad/sec ไปเป็นประมาณ 30,000 rad/sec แสดงในรูปที่ 4.3



รูปที่ 4.3 แสดง Open Loop Gain ของ Nominal plant และ Shaped Plant

กำหนดค่าพารามิเตอร์ในการรัน GA และตัวควบคุมดังนี้ population size = 500, operator probability: cross over=0.6, mutation=0.05, maximum generation = 200 $K_p, K_i, K_d, t_d, x_{1\text{-}2} \in [0, 10000]$, $K_{a\text{-}f} \in [0, 20000]$ ผลการรันตามขั้นตอนในหัวข้อ 3.3 เป็นดังนี้



รูปที่ 4.4 การลู่เข้าคำตอบ

ระบบจะลู่เข้าที่ Generation 45th และได้ค่า stability margin เท่ากับ 0.645 ผลการทดลองและการจำลองการทำงานเป็นไปดังรูป ตัวควบคุมที่สังเคราะห์ได้เป็นดังนี้

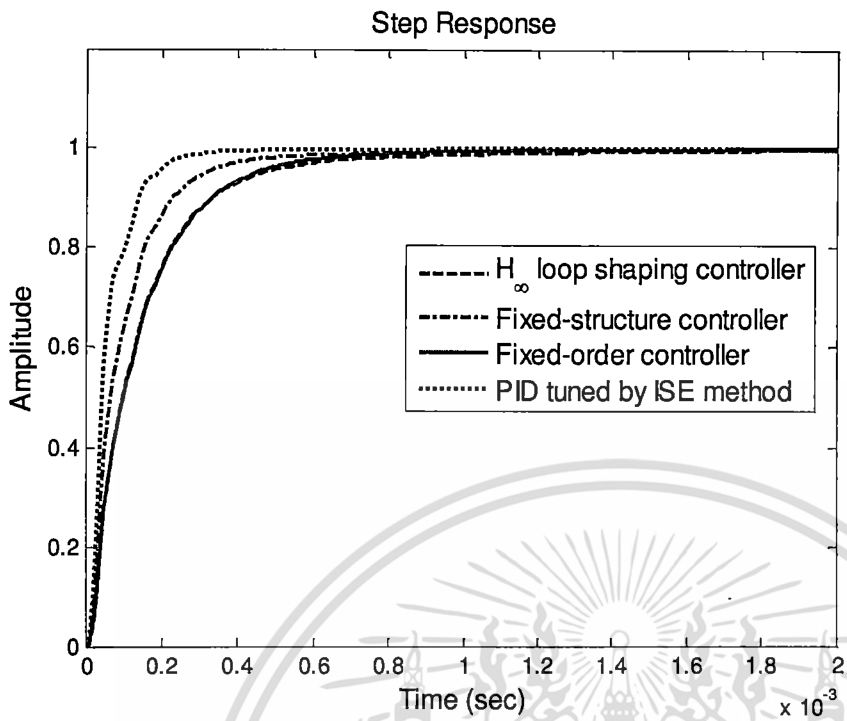
$$K(p) = 5.066 + \frac{4488}{s} + \frac{0.335s}{3.06s+1}$$

อย่างไรก็ตาม เมื่อออกแบบตัวควบคุมแบบเทคนิค H infinity loop shaping แบบเดิม จะได้ตัวควบคุมดังต่อไปนี้

$$K(s) = W_1 K_\infty W_2 = \frac{(4.17s+3425.8)}{(s+0.001)} \frac{3.99\times10^5(s+850.4)(s^2+7.61\times10^4 s+9.18\times10^9)}{(s+3.73\times10^5)(s+821.1)(s^2+8.46\times10^4 s+1.11\times10^{10})}$$

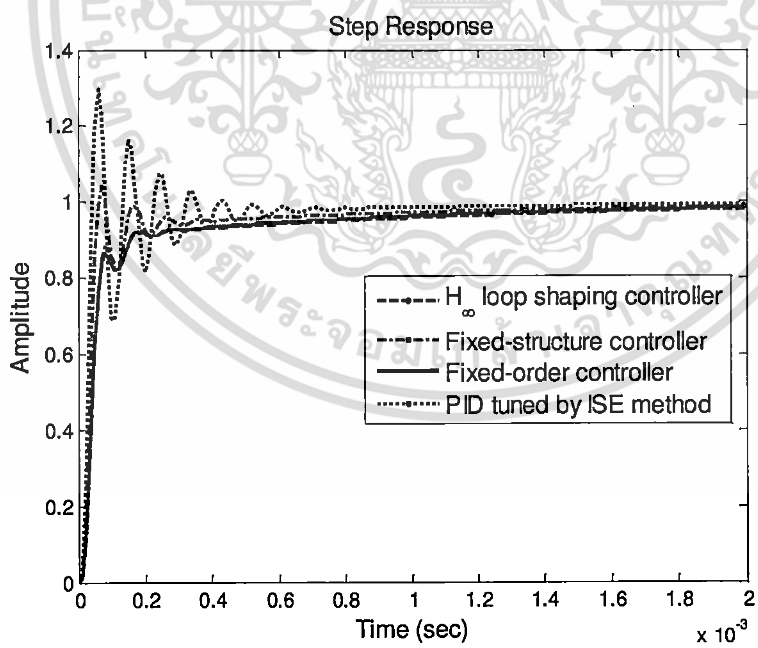
จะเห็นได้ว่า ตัวควบคุมที่นำเสนอมีโครงสร้างง่ายและใช้ได้จริงกว่าเทคนิค H infinity loop shaping แบบเดิม

ผลการจำลองการทำงานด้วยคอมพิวเตอร์เมื่อเปรียบเทียบกับเทคนิค ISE แบบ Model Reference [6] ที่กำหนดให้ reference model เป็น 1st order filter ที่มีค่าคงที่เวลาเท่ากับ 0.0006 ดังนี้



รูปที่ 4.5 แสดงผลตอบสนองทางเวลาของระบบที่ nominal plant

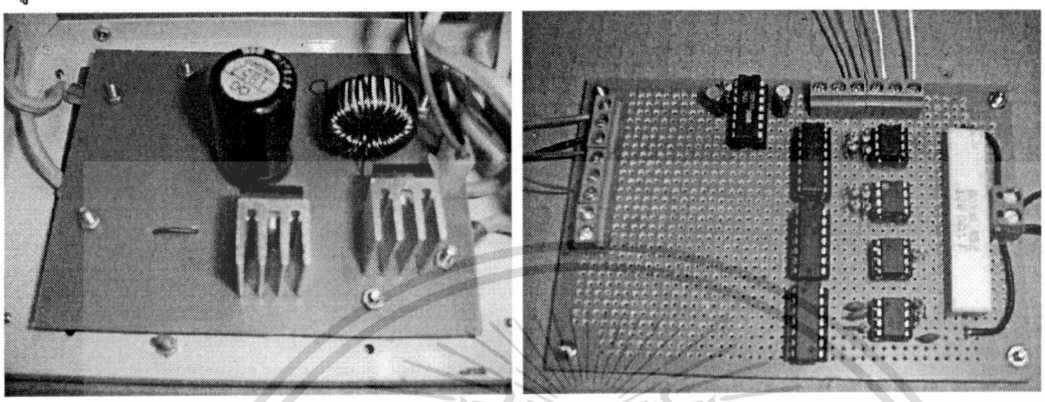
เมื่อระบบมีการเปลี่ยนแปลงพารามิเตอร์ในระบบ ไปในทางที่ทำให้สมรรถนะลดลง $R_L = 0.8\ \Omega$, $L = 130\ \mu H$ and $C = 470\ \mu F$ จะได้ผลตอบสนองดังนี้



รูปที่ 4.6 แสดงผลตอบสนองทางเวลาของระบบที่ perturbed plant

จากรูปที่ 4.6 จะเห็นได้ว่า ระบบที่นำเสนอจะเกิด overshoot น้อยและsettling time เร็วกว่า เมื่อเทียบกับ เทคนิค PID ที่จูนด้วย ISE Method ซึ่งเป็นเทคนิคที่นิยมใช้ เทคนิคที่นำเสนอได้ผลตอบสนองคล้ายกับเทคนิคแบบ H infinity loop shaping แต่ลำดับกับโครงสร้างของเทคนิคที่นำเสนอง่ายและนำไปใช้ได้จริง

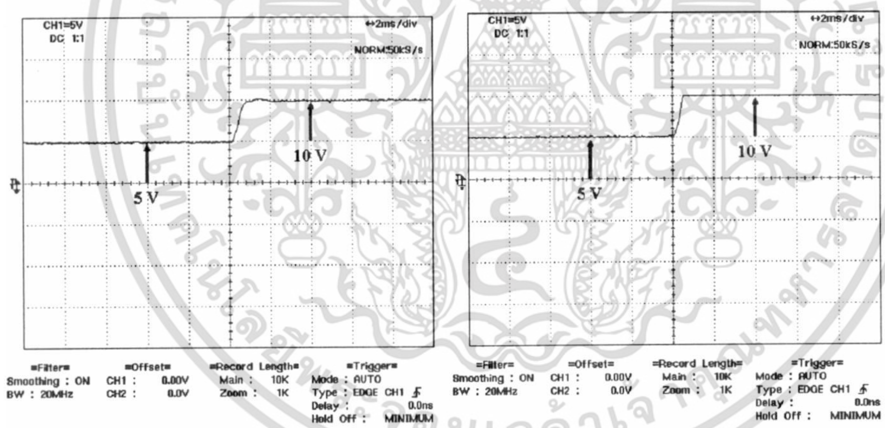
รูปที่ 4.7 แสดงส่วนหนึ่งของวงจรที่สร้างจริง



ภาคกำลัง ภาคควบคุม

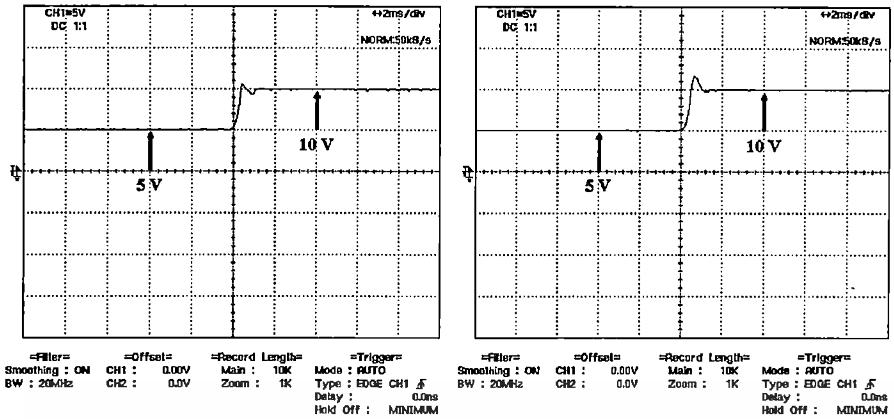
รูปที่ 4.7 ส่วนหนึ่งของวงจรที่ออกแบบและสร้างขึ้น

ผลการทดลองแสดงในรูปต่อไปนี้



(ก) เทคนิคแบบที่นำเสนอ (ข) เทคนิคแบบ ISE

รูปที่ 4.8 ผลการทดลองที่ nominal plant



รูปที่ 4.9 ผลการทดลองที่ perturbed plant

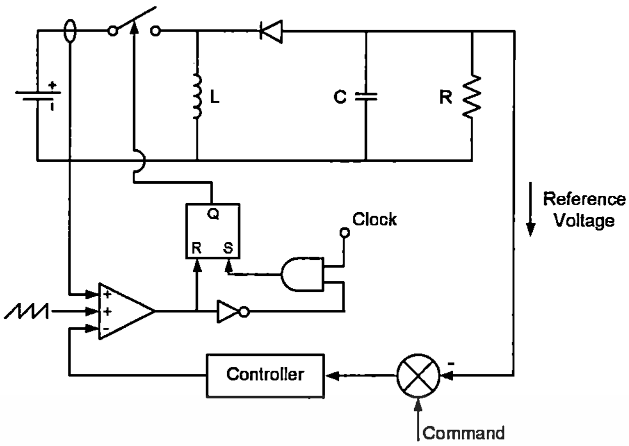
จากผลในรูปที่ 4.8และ 4.9 พบว่า ผลการทดลองใกล้เคียงกับผลการจำลองการทำงานด้วยคอมพิวเตอร์ ระบบที่นำเสนอมี Overshoot ที่ nominal plant และ Perturbed plant ใกล้เคียงกันในขณะที่ระบบที่ออกแบบด้วย ISE นั้น มี Overshoot เกิดขึ้นมากที่ perturbed plant

4.2 ระบบควบคุมสำหรับวงจร Buck Boost Converter แบบ PCMC Mode

วงจรทอนทบระดับแรงดัน (Buck Converter) ที่เป็นแบบโหมดกระแสยอด (Peak Current Mode) จะมีวงจรที่ง่ายและมีอุปกรณ์น้อยกว่าแบบ ACMC จะมีฟังก์ชันถ่ายโอนของวงจรทอนทบระดับแรงดันแบบโหมดกระแสเฉลี่ยจากกระแสอ้างอิง i_r ไปยังแรงดันเอาต์พุต u_o ดังนี้

$$\frac{du_o}{di_r} = R_L \frac{V_i}{V_i + 2V_o} \frac{(1 - \frac{s \cdot L}{R_L} \cdot \frac{V_o}{V_i} \cdot \frac{V_o + V_i}{V_o})}{(1 + s \cdot C \cdot R_L \cdot \frac{V_o + V_i}{2V_o + V_i})} \tag{4.6}$$

ค่า R_L คือ โหลด, V_o แรงดันเอาท์พุท, V_i คือ แรงดันอินพุท, L ค่าความเหนี่ยวนำของวงจร, C ตัวเก็บประจุ, f_{sw} ความถี่การสวิตชิ่ง



รูปที่ 4.10 แสดงภาพวงจรทอนทบระดับแรงดันแบบโหมดกระแส

โดยในงานวิจัยนี้ กำหนดพารามิเตอร์ของวงจรทอนระดับแรงดันต่างๆ ดังนี้

Table 2 Chosen converter's parameter and considered variation ranges

Parameter	Name	Nominal Value
R_L	Load Resistant	40 Ω
V_o	Output Voltage	30 V
V_i	Input Voltage	12 V
L	Inductance	100 μH
C	Capacitor	470 μF
f_{sw}	Switching frequency	100 kHz

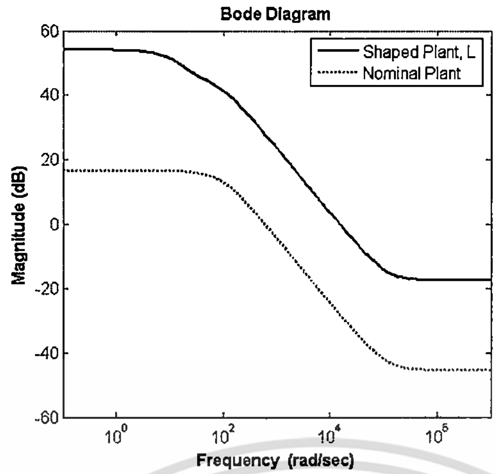
เมื่อแทนค่าพารามิเตอร์ต่างๆ ของวงจรทอนทบระดับแรงดัน จะได้ฟังก์ชันถ่ายโอน ดังสมการที่ (4.7)

$$G_o = \frac{(-0.0042s+480)}{(0.7896s+72)} \tag{4.7}$$

เลือก Weight W1 เป็น

$$W_1 = 25\frac{(s+30)}{(s+10)}$$

ด้วย Weight นี้จะทำให้ระบบมีค่า แบนด์วิดท์เพิ่มจาก 600 rad/sec ไปเป็นประมาณ 15,000 rad/sec แสดงในรูปที่ 4.11



รูปที่ 4.11 แสดง Open Loop Gain ของ Nominal plant และ Shaped Plant

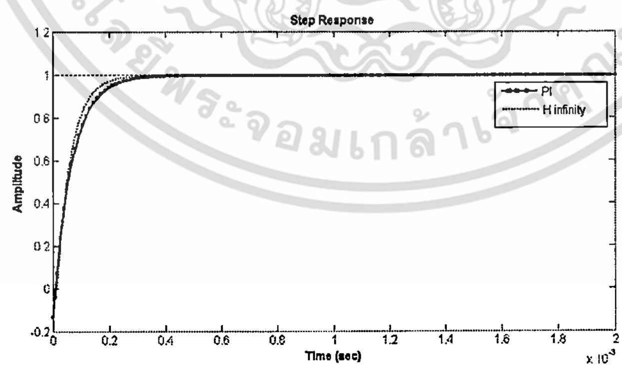
กำหนดค่าพารามิเตอร์ในการรัน GA และตัวควบคุมดังนี้ $K_p \in [0,200]$, $K_i \in [0,1000]$, population size = 100, crossover probability =0.7, mutation probability =0.25, และ maximum generation = 30 ผลการรันตามขั้นตอนในหัวข้อ 3.3 เป็นดังนี้

$$K(p)^* = 21.88 + \frac{989.7}{s}$$

ค่าตัวควบคุมที่ได้ทำให้ระบบมี stability margin เท่ากับ 0.69 อย่างไรก็ตาม เมื่อออกแบบตัวควบคุมแบบเทคนิค H infinity loop shaping แบบเดิม จะได้ตัวควบคุมดังต่อไปนี้

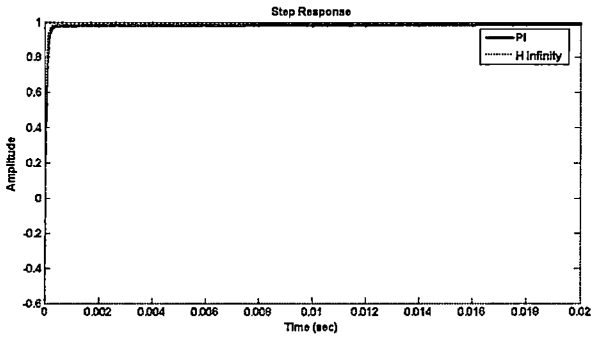
$$K(s) = W_1 K_\infty W_2 = \frac{4.599x10^6 s^2 + 2.763x10^8 s + 4.15x10^9}{s^3 + 1.845x10^5 s^2 + 7.386x10^6 s + 5.541x10^7}$$

จะเห็นได้ว่า ตัวควบคุมที่นำเสนอมีโครงสร้างง่ายและใช้ได้จริงกว่าเทคนิค H infinity loop shaping แบบเดิม ผลการจำลองการทำงานด้วยคอมพิวเตอร์แสดงดังรูปที่ 4.12 และ 4.13



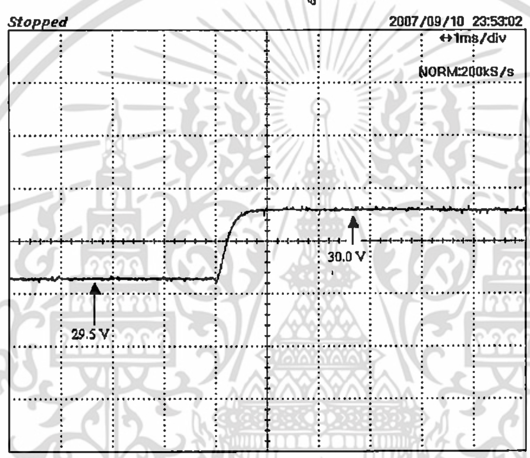
รูปที่ 4.12 แสดงผลตอบสนองทางเวลาของระบบที่ nominal plant

เมื่อระบบมีการเปลี่ยนแปลงพารามิเตอร์ในระบบ ไปในทางที่ทำให้สมรรถนะลดลง R_L= 10 Ω, V_i = 10.8 V, L=120 μH and C=611 μF จะได้ผลตอบสนองดังนี้

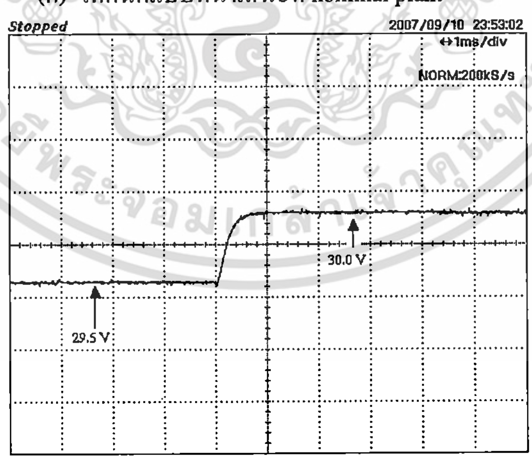


รูปที่ 4.13 แสดงผลตอบสนองทางเวลาของระบบที่ perturbed plant

จะเห็นได้ว่า เทคนิคที่นำเสนอได้ผลตอบสนองคล้ายกับเทคนิคแบบ H infinity loop shaping แต่ลำดับกับโครงสร้าง**ของเทคนิคที่นำเสนอง่ายและนำไปใช้ได้จริง** ผลการทดลองแสดงในรูปต่อไปนี้



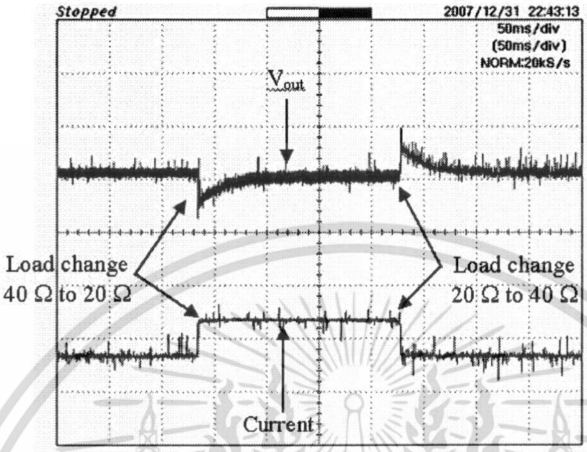
(ก) เทคนิคแบบที่นำเสนอที่ nominal plant



(ข) perturbed plant

รูปที่ 4.14 ผลการทดลอง

จากผลรูปที่ 4.13และ 4.14 พบว่า ผลการทดลองใกล้เคียงกับผลการจำลองการทำงานด้วยคอมพิวเตอร์ ระบบที่นำเสนอมี Overshoot ที่ nominal plant และ Perturbed plant ใกล้เคียงกันรูปที่ 4.15 แสดงผลตอบสนองในการควบคุมระดับแรงดันในขณะที่โหลดเปลี่ยนแปลงทันทีทันใด จากรูปจะเห็นได้ว่าระบบมีผลตอบสนองได้เร็วและคงทนต่อการเปลี่ยนแปลงโหลด

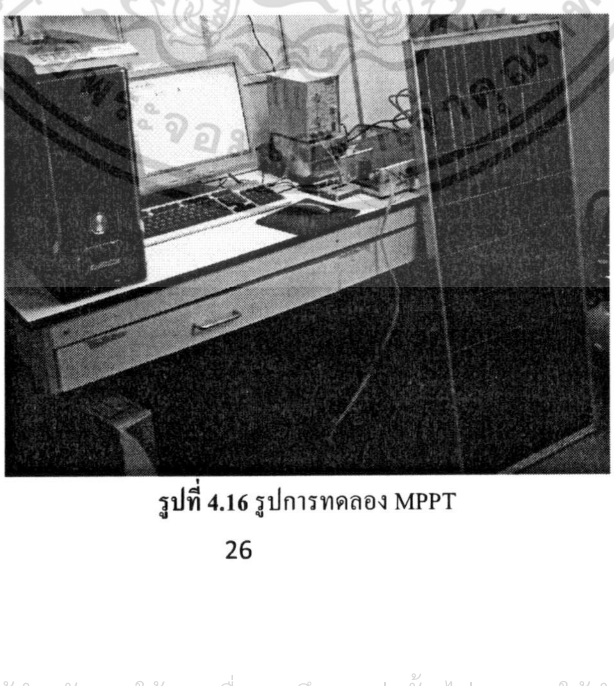


รูปที่ 4.15 ผลการทดลองกรณีโหลดเปลี่ยนแปลงทันทีทันใด

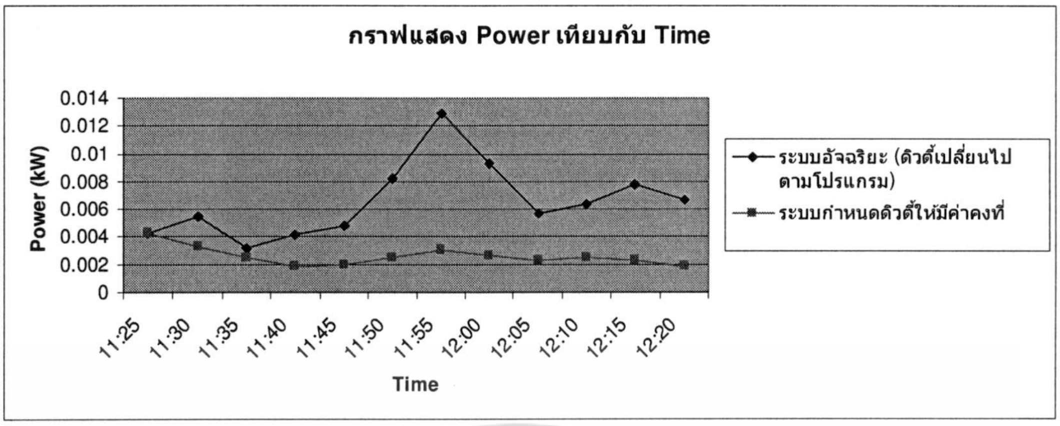
รายละเอียดของงานวิจัยสามารถดูได้จากบทความในภาคผนวก

4.3 ผลอื่นๆ

ในงานวิจัยได้นำไปทดสอบกับระบบ MPPT ด้วย ดังแสดงในรูป4.16 ผลของการรัน MPPT ได้กำลังไฟฟ้ามากกว่า charger แบบที่ไม่มี MPPT ดังแสดงในรูปที่ 4.17 นอกจากนี้ในงานวิจัยนี้ยังได้นำแนวคิดดังกล่าวไปใช้ในระบบเครื่องบิน HIMAT และระบบทางไฟฟ้ากำลัง ดังแสดงในบทความที่ 3 และ 5 ของในภาคผนวกของรายงานวิจัยฉบับนี้



รูปที่ 4.16 รูปการทดลอง MPPT



รูปที่ 4.17 ผลการทำงานของ MPPT

5 สรุปผลการทดลอง

ตัวควบคุมที่ออกแบบขึ้นโดยวิธีที่นำเสนอนี้สามารถทำให้ระบบมีสมรรถนะความคงทนสูง ด้วยขั้นตอนวิธีเชิงพันธุกรรมทำให้การออกแบบชุดควบคุมที่กำหนดโครงสร้างได้ทำได้ง่ายขึ้น โดยอาศัยหลักการจัดสัณฐานวงรอบเอชอินฟินิตี้ (H_∞ infinity) ซึ่งมีดัชนีที่ใช้วัดความคงทนและสมรรถนะจะมีเพียงค่าเดียวคือ ส่วนเผื่อเสถียรภาพ (ε) จากการออกแบบชุดควบคุมในงานวิจัยนี้ พบว่ามีค่าเผื่อเสถียรภาพมากเพียงพอ ซึ่งแสดงให้เห็นว่าตัวควบคุมที่ออกแบบขึ้นนี้สอดคล้องกับข้อกำหนดทางสมรรถนะและความคงทนที่ต้องการ จากผลการทดลองเมื่อมีการเปลี่ยนแรงดันอ้างอิงและมีการเปลี่ยนแปลงโหลดของระบบ ระบบก็ยังมีการตอบสนองที่ดีจากการทดสอบการนำไปใช้กับระบบ MPPT พบว่า สามารถนำไปควบคุมกำลังไฟฟ้าสูงสุดได้

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GA based Fixed Structure H_∞ Loop Shaping Controller for a Buck-Boost Converter

Piyapong Olranthichachat and Somyot Kaitwanidvilai

Abstract— **In this paper, we propose a new technique used to design a robust controller that is not as high-order and complicated as the ones designed by conventional H_∞ loop shaping method. To overcome the problem we proposed an algorithm called *Genetic Algorithm (GA) based fixed-structure H_∞ loop shaping control.* In the approach, GA is adopted to solve the H_∞ loop shaping design problem under a structure specified controller. The performance and robustness of the proposed controller are investigated in a buck-boost converter in comparison with the controller designed by conventional H_∞ loop shaping. Results of simulations demonstrate the advantages of the proposed controller in terms of simple structure and robustness against plant perturbations and disturbances. Experiments are performed to verify the effectiveness of the proposed technique.**

Index Terms— **H_∞ loop shaping , genetic algorithm , buck boost converter**

I. Introduction

DC-DC converters have been widely used in computer hardware and industrial applications. Controlling of these converters is a challenging field because of their intrinsic nature of nonlinear, time-variant systems [1]. In previous research works, the linear models of these converters were derived by using linearization method [2-3]. Some linear control techniques were applied to these converters based on the linear models [1, 4-5]. NAIM, R., *et.al.*[4], applied the H_∞ control to a boost converter. Three controllers; voltage mode, feed-forward and current mode control were investigated and compared the performance. G.C. loannidis and S.N. Manias [5] applied the H_∞ loop shaping control schemes for a buck converter. In their paper, the μ-analysis was used to examine the robust features of the designed controllers. Simone Buso [1] adopted the robust μ-synthesis to design a robust voltage controller for a buck-boost converter with current mode control. The parameter variations in the converter's transfer function were described in term of perturbations of linear fraction transformations (LFT) class.

In DC to DC converter, normally, the controller is designed by using analog circuit. Although the higher control techniques mentioned above are powerful techniques for designing the high performance and robust controller; however, the structure of these controllers is complicated with a high order. It is not easy to implement these controllers in the converters. Nevertheless, the design of analog circuit for these controllers is not feasible. To overcome this problem, fixed-structure controller is investigated. Fixed-structure robust controllers have become an interesting area of research because of their simple structure and acceptable controller order. However, the design of this controller by using the analytical method remains difficult. To simplify this problem, the searching algorithms such as genetic algorithm, particle swarm optimization technique, gradient method, etc., can be employed.

Several approaches to design a robust control for structure specified controller were proposed in [6-8]. In [6], a robust H_∞ optimal control problem with structure specified controller was solved by using genetic algorithm (GA). As concluded in [6], genetic algorithm is a simple and efficient tool to design a structure specified H_∞ optimal controller. Bor-Sen.Chen. *et. al.*[7], proposed a PID design algorithm for mixed H_2/H_∞ control. In their paper, PID controller parameters were tuned in the stability domain to achieve mixed H_2/H_∞ optimal control. A similar work was proposed in [8] by using the intelligent genetic algorithm to solve the mixed H_2/H_∞ optimal control problem. The techniques in [6-8] are based on the concept of H_∞ optimal control which two appropriate weights for both the uncertainty of the model and the performance are essentially chosen. A difficulty with the H_∞ optimal control approach is that the appropriate selection of close-loop objectives and weights is not straightforward. In robust control, H_∞ loop shaping which is a simple and efficient technique for designing a robust controller can be alternatively used to design the robust controller for the system. Uncertainties in this approach are modeled as normalized co-prime factors; this uncertainty model does not represent actual physical uncertainty, which usually is unknown in real problems. This technique requires only two specified weights, pre-compensator and post-compensator, for shaping the nominal plant so that the desired open loop shape is achieved. Fortunately, the selection of such weights is based on the concept of classical loop shaping which is a well known technique in controller design. By the reasons mentioned above, this technique is simpler and more intuitive than other robust control techniques. However, the controller designed by H_∞ loop shaping is still complicated and has high order. To overcome this problem, in this paper, we propose a

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fixed-structure H_∞ loop shaping control to design a robust controller for a buck boost converter. In the proposed technique, the controller structure is firstly specified and the genetic algorithm is then used to evaluate the control's parameters. Simulation and experimental results show the advantages of simple structure, lower order and robustness of the proposed controller.

The remainder of this paper is organized as follows. Converter dynamics are described in section II. H_∞ loop shaping and the proposed technique are discussed in section III. Section IV demonstrates the design example and results. Finally, section V concludes the paper with some final remarks.

II. Converter Modeling

A typical circuit of buck-boost converter with current mode control is shown in Fig. 1. The dynamic model of this converter from the current reference (i_r) to output voltage (u_0) is given by [2-3]

$$\frac{du_o}{di_r} = R_L \frac{V_i}{V_i + 2V_o} \frac{(1 - \frac{s \cdot L}{R_L} \cdot \frac{V_o}{V_i} \cdot \frac{V_o + V_i}{V_o})}{(1 + s \cdot C \cdot R_L \cdot \frac{V_o + V_i}{2V_o + V_i})} \quad (1)$$

Where R_L is the nominal load resistant, V_o is the nominal output voltage, V_i is the nominal input voltage, L is the inductance of an inductor used in the circuit, C is the capacitance, f_{sw} is the switching frequency.

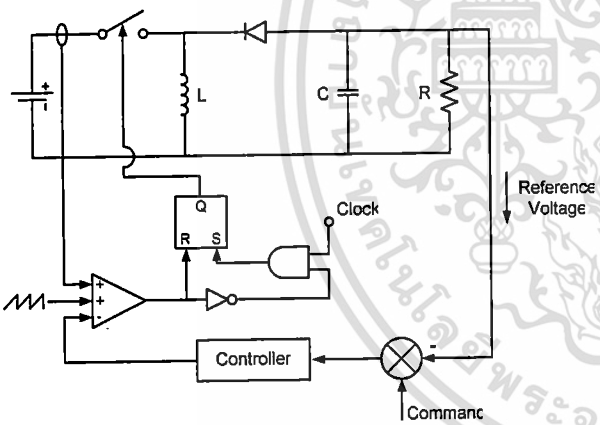


Fig. 1. Buck boost converter with current mode control.

The accuracy of this model has been proved to be accepted, at least in frequency of interest in this application [2-3].

III. H_∞ Loop Shaping Control and Proposed Technique

This section illustrates the concepts of the standard H_∞ loop shaping control and the proposed technique.

A. Standard H_∞ Loop Shaping

H_∞ loop shaping control [9] is an efficient method to design a robust controller. This approach requires only a desired open loop shape in frequency domain. Two weighting functions, W_1 (pre-compensator) and W_2 (post-compensator), are specified to shape the original plant G_o. In this approach, the shaped plant is formulated as normalized coprime factor, which separates the plant G_s into normalized nominator N_s and denominator M_s factors. Fig. 2 shows the coprime perturbed plant and robust stabilization used in this approach.

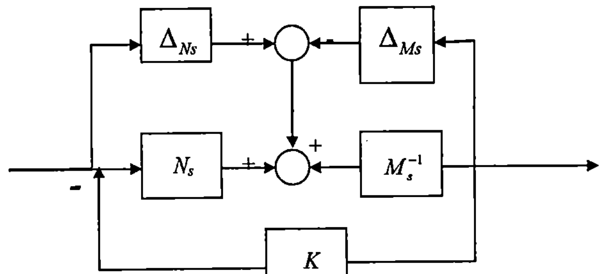


Fig. 2. Co-prime factor robust stabilization problem.

If the shaped plant $G_s = W_2 G_o W_1 = N_s M_s^{-1}$, then a perturbed plant is written as [9]

$$G_\Delta = (N_s + \Delta_{Ns})(M_s + \Delta_{Ms})^{-1} \quad (2)$$

Where Δ_{Ns} and Δ_{Ms} are stable, unknown representing the uncertainty satisfying $\left\| \Delta_{Ns}, \Delta_{Ms} \right\|_\infty \le \varepsilon$,

ε is the uncertainty boundary, called stability margin.

According to the standard procedure of H_∞ loop shaping, the following steps can be applied to design the H_∞ loop shaping controller.

Step 1 Shape the singular values of the nominal plant G_o by using a pre-compensator W_1 and/or a post-compensator W_2 to get the desired loop shape. W_2 can be chosen as an identity matrix, since we can neglect the sensor noise effect when the use of good sensor is assumed [10]. Weight selection is very important for the design. Typically, weight W_1 and W_2 are selected such that the open loop of the shaped plant has the following conflict properties:

- To achieve a good performance tracking, good disturbance rejection, large open loop gain (normally at low frequency range) is required.
- To achieve a good robust stability and sensor noise rejection, small open loop gain (normally at high frequency range) is required.

There are some guidelines for the weight selection in [10]. In SISO system, the weighting functions W_1 and W_2 can be chosen as

$$W_1 = K_W \frac{s + a}{s + b} \text{ and } W_2 = 1 \quad (3)$$

Where K_w, a and b are positive values

Step 2 Minimize ∞-norm of the transfer matrix T_{zw} over all stabilizing controllers K, to obtain an optimal cost γ_{opt}, as [10]

$$\gamma_{opt} = \varepsilon_{opt}^{-1} = \inf_{stabK} \left\| \begin{bmatrix} I \\ K \end{bmatrix} (I + G_s K)^{-1} M_s^{-1} \right\|_\infty \quad (4)$$

ε_{opt} << 1 indicates that W_1 or W_2 designed in step 1 are incompatible with robust stability requirement. If ε_{opt} is not

(Advance online publication: 20 August 2008)

satisfied (ε_{opt} << 1), then return to step 1, adjust W_1.

Step 3 Select $\varepsilon < \varepsilon_{opt}$ and then synthesize a controller K_∞ that satisfies

$$\|T_{zw}\|_\infty = \left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (I + G_s K_\infty)^{-1} M_s^{-1} \right\|_\infty \le \varepsilon^{-1} \quad (5)$$

Controller K_∞ is obtained by solving the optimal control problem. See [11] for more details.

Step 4 Final controller (K) follows

$$K = W_1 K_\infty W_2 \quad (6)$$

B. Genetic Algorithm based Fixed-Structure H_∞ Loop Shaping Optimization

The controller, which is derived from H_∞ loop shaping method, is complicated and high-order. It is difficult to apply this controller in real works. Nowadays, the fixed-structure robust controller becomes an interesting research area because of their advantages in simple structure and acceptable controller's order. In this paper, the genetic searching algorithm is adopted to solve this problem. Although the proposed controller is structured, it still retains the entire robustness and performance guarantee as long as a satisfactory uncertainty boundary ε is achieved. The proposed algorithm is explained as following.

Assume that the predefined structure controller $K(p)$ has a satisfied parameters p. Based on the concept of H infinity loop shaping, optimization goal is to find parameters p in controller $K(p)$ that minimize infinity norm $\|T_{zw}\|_\infty$. From (6), the controller $K(p)$ can be written as

$$K(p) = W_1 K_\infty W_2 \quad (7)$$

Assume that W_1 and W_2 are invertible, then

$$K_\infty = W_1^{-1} K(p)\, W_2^{-1} \quad (8)$$

the weight $W_2 = I$ which implies that sensor noise is negligible and not considered [10]. Thus,

$$K_\infty = W_1^{-1} K(p) \quad (9)$$

By Substitution of (9) into (5), then the ∞-norm of the transfer function matrix from disturbances to states, $\|T_{zw}\|_\infty$, which is subjected to be minimized can be written as

$$J_{cost} = \gamma = \|T_{zw}\|_\infty = \left\| \begin{bmatrix} I \\ W_1^{-1} K(p) \end{bmatrix} (I + G_s W_1^{-1} K(p))^{-1} M_s^{-1} \right\|_\infty \quad (10)$$

In this paper, GA is adopted to find the optimal control parameters p^* in the stabilizing controller $K(p)$ such that the $\|T_{zw}\|_\infty$ is minimized. The optimization problem can be written as

$$\text{Minimize} \quad \left\| \begin{bmatrix} I \\ W_1^{-1} K(p) \end{bmatrix} (I + G_s W_1^{-1} K(p))^{-1} M_s^{-1} \right\|_\infty \quad (11)$$

Subject to

$$p_{i,\min} < p_i < p_{i,\max}$$

Where $p_{i,\min}$ and $p_{i,\max}$ are the lower and upper bound values of the parameter p_i in controller $K(p)$, respectively.

Genetic Algorithms

Our proposed technique uses GA to solve the optimization problem in (11). GA is well known as a biologically inspired class of algorithms that can be applied to any nonlinear optimization problem. This algorithm applies the concept of chromosomes, and the operations of crossover, mutation and reproduction. At each step, called generation, fitness values of all chromosomes in population are calculated. Chromosome, which has the maximum fitness value (minimum cost value), is kept as a solution in the current generation and passed to the next generation. The new population of the next generation is obtained by performing the genetic operators such as crossover, mutation, and reproduction. Crossover randomly selects a site along the length of two chromosomes, and then splits the two chromosomes into two pieces by breaking them at the crossover site. The new chromosomes are then formed by matching the headpiece of one chromosome with the tailpiece of the other. Mutation operation forms a new chromosome by randomly changing value of a single bit in the chromosome. Reproduction operation forms a new chromosome by just copying the old chromosome. Chromosome selection in genetic algorithm depends on the fitness value. High fitness value means high chance to be selected. Operation type selection; mutation, reproduction, or crossover, depends on the pre-specified operation's probability.

Chromosome in genetic population is coded as binary number. However, for the real number problem, decoding binary number to floating number is applied [12]..

Our proposed algorithm is summarized as

Step 1 Shape the singular values of the nominal plant G_o by W_1 and W_2. Then evaluate the ε_{opt} using (4). If $\varepsilon_{opt} < 0.25$, then go to step 1 to adjust the weight W_1.

Step 2 Select a controller structure $K(p)$ and initialize several sets of parameters p as population in the 1st generation. Define the genetic parameters such as initial population size, crossover and mutation probability, maximum generation, etc.

Step 3 Evaluate the cost function J_{cost} of each chromosome using (10). Assign $J_{cost} = 100$, or large number if $K(p)$ does not meet the constraints in our optimization problem. The fitness value is assigned as $\frac{1}{J_{cost}}$. Select the chromosome with minimum cost function as a solution in the current generation. For the first generation, Gen = 1.

Step 4 Increment the generation for a step.

Step 5 While the current generation is less than the maximum generation, create a new population using genetic operators and go to step 3. If the current generation is the maximum generation, then stop.

Step 6 Check performances in both frequency and time domains. If the performance is not satisfied, such as too low ε (too low fitness function), then go to step 3 to change the control structure. Low ε indicates that the selected control structure is not suitable for the problem.

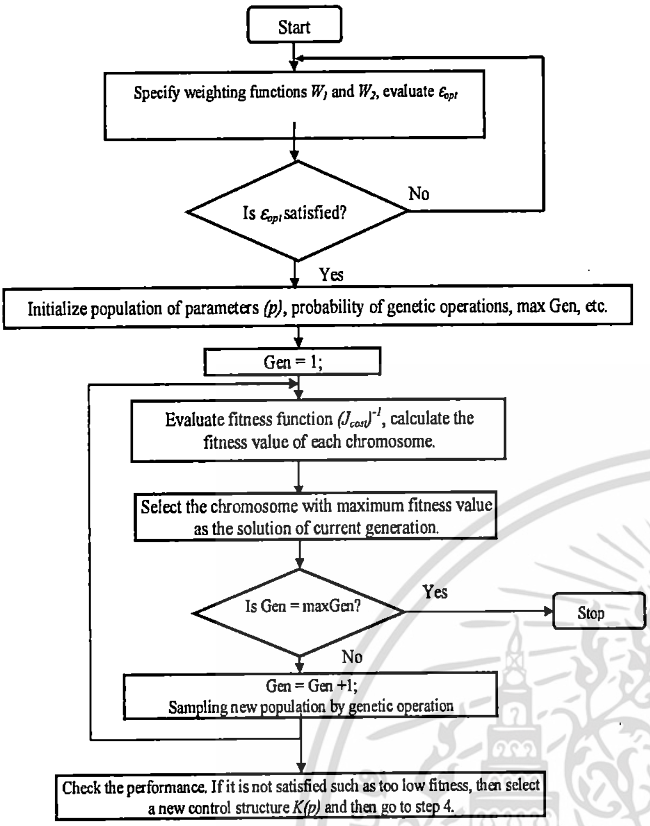


Fig. 3. Flow chart of the proposed design procedure.

IV. Simulation and Experimental Results

In this paper, a buck-boost converter designed for a photovoltaic system is studied. Converter's parameters and considered variation ranges used in this paper are given in Table 1.

Table 1 Converter's parameters and considered variation ranges.

Parameter	Name	Nominal Value
R_L	Load Resistant	40 Ω
V_o	Output Voltage	30 V
V_i	Input Voltage	12 V
L	Inductance	100 µH
C	Capacitor	470 µF
f_{sw}	Switching frequency	100 kHz

By (1), the nominal transfer function is found to be

$$G_o = \frac{(-0.0042s+480)}{(0.7896s+72)} \tag{12}$$

Both H∞ loop shaping control and our proposed technique are applied to this converter. Firstly, we design a controller by the conventional H∞ loop shaping procedure. In this case, W_1 is selected as

$$W_1 = 25\frac{(s+30)}{(s+10)} \tag{13}$$

W_2 is chosen as 1 since we neglect the sensor noise effect when the use of good sensor is assumed. Fig. 4 (a) shows the plot of open loop shape of nominal plant and shaped plant. As seen in this figure, the bandwidth of the nominal plant is about 600 rad/sec. With these weighting functions, bandwidth of the desired control system is increased to 15,000 rad/sec. Significant performances and robustness improvement are carried out by these weighting functions.

The shaped plant is written as

$$G_s = L = W_1 G W_2 = 25\frac{(s+30)(-0.0042s+605.6)}{(s+10)(0.9963s+72)} \tag{14}$$

By applying the H∞ loop shaping method, the optimal stability margin (ε_{opt}) is founded at 0.708 ($\gamma_{opt}=1.4123$). This value indicates that the selected weighting function is compatible with the robust stability requirement. The ε = 0.66123 (γ=1.5123), which is less than the optimal stability margin, is chosen to synthesis the controller. Based on the conventional technique is section II, the conventional H∞ loop shaping controller is synthesized as following

$$K(s) = W_1 K_\infty W_2 = \frac{4.599x10^6 s^2 + 2.763x10^8 s + 4.15x10^9}{s^3 + 1.845x10^5 s^2 + 7.386x10^6 s + 5.541x10^7} \tag{15}$$

As shown in (15), the controller is 3th order controller and complicated structure.

Next, PI controller is investigated as a fixed-structure controller. The controller structure is expressed in (16). K_p and K_i are parameters that will be evaluated.

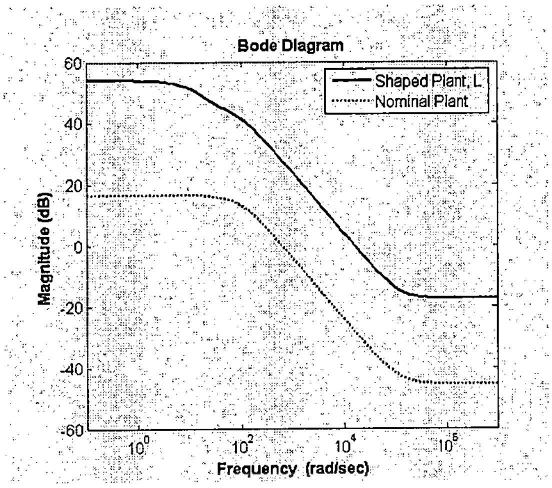
$$K(p) = K_p + \frac{K_i}{s} \tag{16}$$

Select the controller parameters, their ranges, and genetic algorithms parameters as following: $K_p \in [0,200]$, $K_i \in [0,1000]$, population size = 100, crossover probability =0.7, mutation probability =0.25, and maximum generation = 30. An optimal solution is obtained after 18 generations. The optimal solution is shown in (17), which has stability margin (ε) of 0.65918(γ=1.5171).

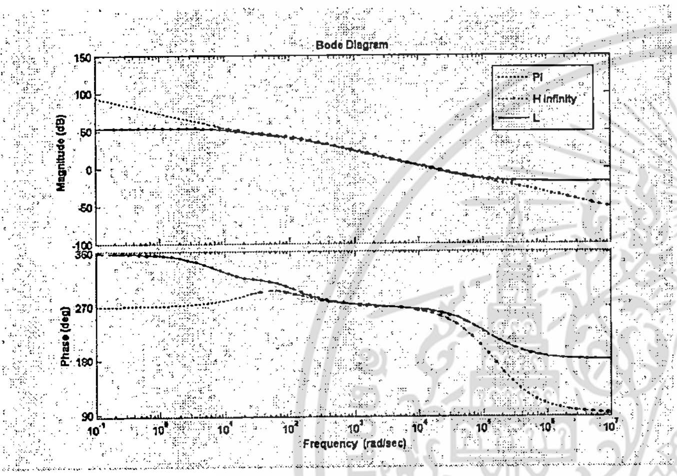
$$K(p)^* = 21.88 + \frac{989.7}{s} \tag{17}$$

Fig. 5 shows plots of convergence of cost function J_{cost} versus generations by genetic algorithm. As seen in this figure, the optimal fixed-structure controller provides the satisfied stability margin at 0.65918(γ=1.5171).

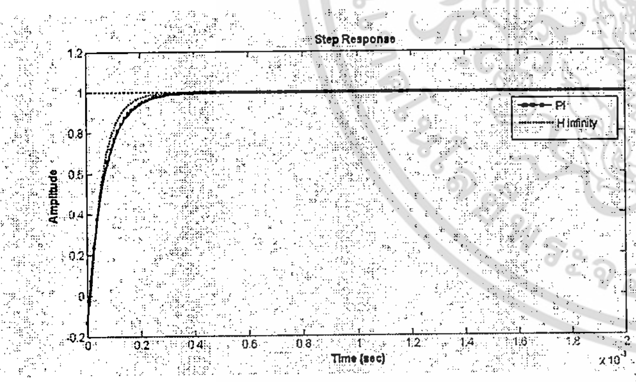
(Advance online publication: 20 August 2008)



(a)



(b)



(c)

Fig. 4. (a) Bode plots of the nominal plant and the shaped plant (desired loop shape, L) (b) The desired loop shape and the loop shape by the conventional H_∞ loop shaping and the proposed PI, (c) Step responses by the proposed PI and H_∞ loop shaping controllers.

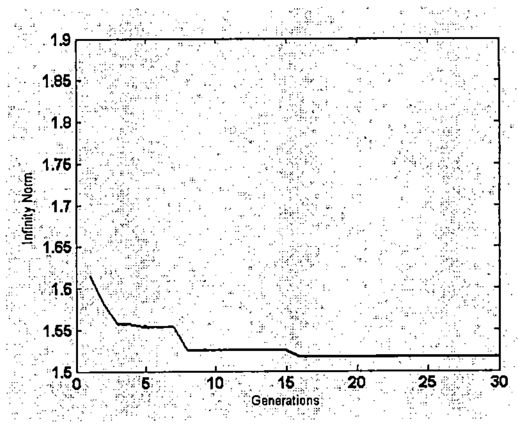


Fig. 5 Cost functions J_{cost} versus iteration in genetic algorithm.

The open loop bode diagrams of the nominal and shaped plants are shown in Fig. 4(a). As shown in this figure, at low frequency, the open loop gain of shaped plant is much larger than that of the nominal plant. This makes the designed system has good performance tracking and good disturbance rejection. Open loop bode diagrams are plotted in Fig. 4(b) to verify the proposed algorithm. It is clearly shown that the loop shapes of H_∞ control and PI are close to the desired loop shape. Fig. 4(c) shows the step responses of the optimal solutions from the proposed robust PI and the conventional H_∞ controllers. As shown in this figure, the settling time of all responses is about 350 µsec.

To verify the robust performance, we change the converter's parameters as: R_L= 10 Ω, V_i = 10.8 V, L=120 µH and C=611 µF. The designed controller in (15) and (17) is adopted to control this perturbed plant. Obviously, this condition (increase the L and C and decrease the load and input voltage) is worse than the nominal condition. In this case, for simulation, the plant is changed to

$$G = \frac{(-0.004896s + 129.6)}{(0.2938s + 70.8)} \qquad (18)$$

Fig. 6 shows the step responses of all controllers in the perturbed plant. The responses are almost the same as the responses in the nominal plant with some different in the setting time. The results show that the designed system from the proposed controller and H_∞ loop shaping has a good performance and robustness.

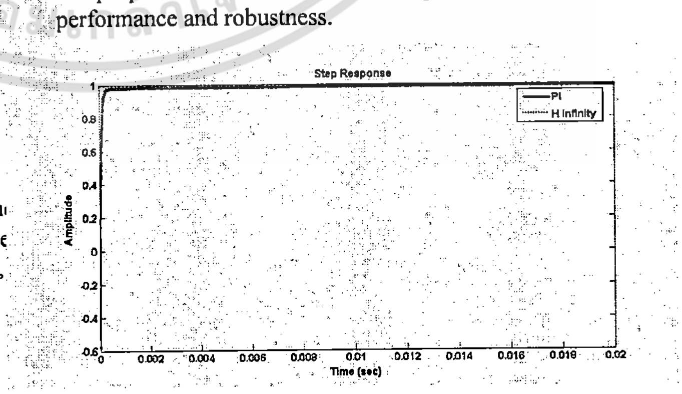


Fig. 6 Step responses in the perturbed plant.(R_L= 10 Ω, V_i = 10.8 V, L=120 µH and C=611 µF).

Some experiments are performed to verify the effectiveness of the proposed controller. The nominal values in Table 1 are used to design a buck boost converter with current mode control. A proposed controller, robust PI controller in (17) is used to control the converter. Fig. 7 shows the experimental result of step response of the proposed controller. The settling time of the response is about 350 μsec. As seen in Fig. 4(c) and Fig. 7, the response of experimental result is almost the same as that of the simulation result.

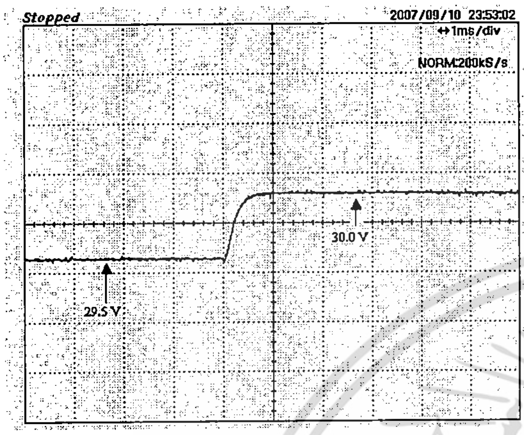


Fig. 7 Step response in the closed loop in nominal conditions for proposed PI controller.

To verify the robust performance of the system, an experiment is performed. The component values and operating points of converter are changed to: R_L= 10 Ω, V_i = 10.8 V, L=120 μH and C=611 μF. The controller from the previous experiment is used to control this perturbed plant. The performance is verified by using the step response. As shown in Fig. 8, the step response is almost the same as the response in nominal conditions. This response is over damp response with a small different in the settling time. Experimental results verify that the proposed controller can be applied for the buck-boost converter to achieve a good robust performance.

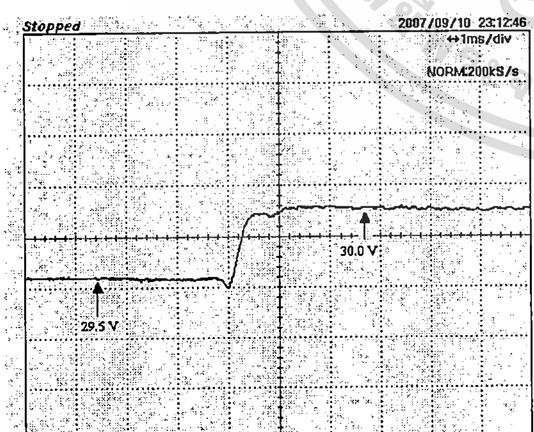


Fig. 8 Step response in the closed loop in perturbed conditions for the proposed PI controller.

To verify the robust against the sudden change of load, an experiment were performed. As shown in Fig.9, when the load is abruptly changed, the proposed controller can maintain the desired voltage.

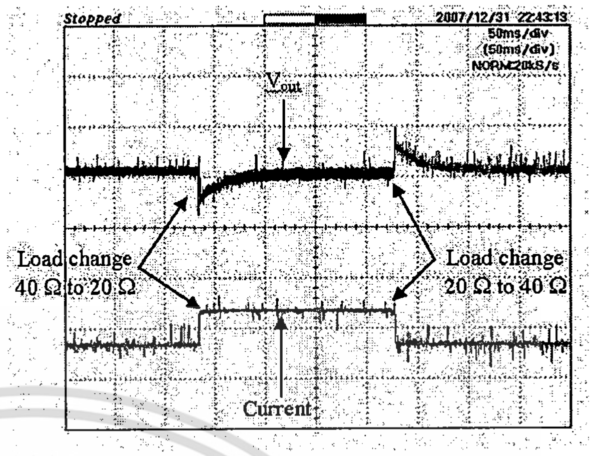


Fig.9 response of propose controller when the load change 40 Ω to 20 Ω.

V. Conclusion

Both of H∞ loop shaping and the proposed technique can be applied to design a robust controller for a buck boost converter. However, the proposed approach significantly improves in practical control viewpoint by simplifying the controller structure, reducing the controller order and retaining the robust performance. Although the proposed controller is structured, it still retains the entire robustness and performance guarantee as long as a satisfactory uncertainty boundary ε is achieved. Structure of controller in the proposed technique is selectable. This is desirable, especially in the DC-DC converter which analog circuit is normally used to design the controller. In conclusion, by combining of the approaches, genetic algorithms and H∞ loop shaping; fixed-structure controller design can be designed. Implementation in buck-boost converter assures that the proposed technique is valid and flexible.

Acknowledgment

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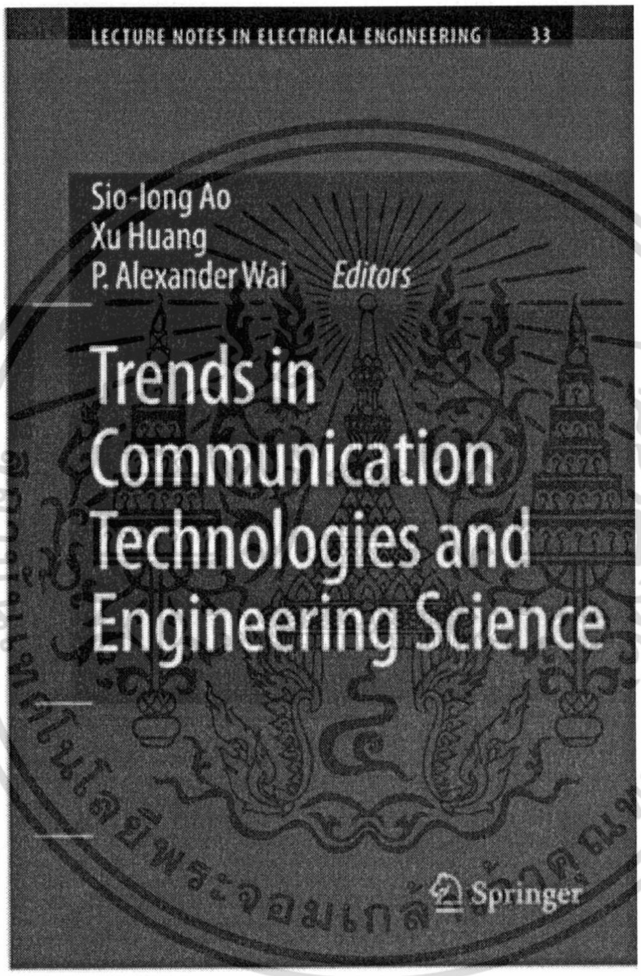
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Preface

A large international conference on Advances in Communication Technologies and Engineering Science was held in Hong Kong, March 19–21, 2008, under the International MultiConference of Engineers and Computer Scientists (IMECS 2008). The IMECS 2008 is organized by the International Association of Engineers (IAENG). IAENG is a non-profit international association for the engineers and the computer scientists, which was found originally in 1968 and has been undergoing rapid expansions in recent few years. The IMECS conferences serve as good platforms for the engineering community to meet with each other and to exchange ideas. The conferences have also stroke a balance between theoretical and application development. The conference committees have been formed with over two hundred committee members who are mainly research center heads, faculty deans, department heads, professors, and research scientists from over 30 countries. The conferences are truly international meetings with a high level of participation from many countries. The response that we have received for the congress is excellent. There have been more than five hundred manuscript submissions for the IMECS 2008. All submitted papers have gone through the peer review process and the overall acceptance rate is 56.03%.

This volume contains revised and extended research articles written by prominent researchers participating in the conference. Topics covered include communications theory, communications protocols, network management, wireless networks, telecommunication, electronics, power engineering, control engineering, signal processing, and industrial applications. The book will offer the states of arts of tremendous advances in communication systems and engineering science and also serve as an excellent reference work for researchers and graduate students working with/on communication technologies and engineering science.

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Chapter 14
Fixed Structure Robust Loop Shaping Controller for a Buck-Boost Converter Using Evolutionary Algorithm

S. Kaitwanidvilai, A. Jangwanitlert, I. Ngarmroo, W. Khanngern and S. Karnprachar

Abstract In this paper, we propose a new technique used to design a robust controller that is not as high-order and complicated as the ones designed by conventional H_{∞} loop shaping method. The proposed algorithm is called *Genetic Algorithm (GA) based fixed-structure H_{∞} loop shaping control.* In the approach, GA is adopted to solve the H_{∞} loop shaping design problem under a structure specified controller. The performance and robustness of the proposed controller are investigated in a buck-boost converter in comparison with the controllers designed by conventional H_{∞} loop shaping and conventional ISE method. Results of simulations demonstrate the advantages of the proposed controller in terms of simple structure and robustness against plant perturbations and disturbances. Experiments are performed to verify the effectiveness of the proposed technique.

Keywords H_{∞} loop shaping · Robust controller · Genetic algorithm · Buck-boost converter

14.1 Introduction

DC–DC converters have been widely used in computer hardware and industrial applications. Controlling of these converters is a challenging field because of their intrinsic nature of nonlinear, time-variant systems [1]. In previous research works, the linear models of these converters were derived by using linearization method [2, 3]. Some linear control techniques were applied to these converters based on the linear models [1, 4, 5]. Naim et al. [4] applied the H_{∞} control to a boost converter. Three controllers; voltage mode, feed-forward and current mode control were investigated and compared the performance. G.C. Ioannidis and S.N. Manias [5] applied the H_{∞} loop shaping control schemes for a buck converter. In their paper, the

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μ-analysis was used to examine the robust features of the designed controllers. Simone Buso [1] adopted the robust μ-synthesis to design a robust voltage controller for a buck-boost converter with current mode control. The parameter variations in the converter's transfer function were described in term of perturbations of linear fraction transformations (LFT) class.

The controllers in DC to DC converters are usually designed using analog circuit. Although the controllers designed by the techniques mentioned earlier are robust, and high performance, they are complicated and high order, thus they are difficult to be implemented in the converters. Nevertheless, the design of analog circuit for these controllers is not feasible. To solve this problem, fixed-structure controller is investigated. Fixed-structure robust controllers have become an interesting area of research because of their simple structure and acceptable controller order. However, it is difficult to design this controller using analytical method. Algorithms such as genetic algorithm, particle swarm optimization, and gradient method can be employed to simplify the design of this controller.

Several approaches to design a robust control for structure specified controller were proposed in Bor-Sen Chen and Yu-Min Cheng [6], Bor-Sen Chen [7], and Shinn-Jang Ho et al. [8]. In Bor-Sen Chen and Yu-Min Cheng [6], a robust $_\infty$ optimal control problem with structure specified controller was solved by using genetic algorithm (GA). As concluded in this paper, genetic algorithm is a simple and efficient tool to design a structure specified $_\infty$ optimal controller. Bor-Sen Chen et al. [7], proposed a PID design algorithm for mixed $_2/_\infty$ control. In their paper, PID controller parameters were tuned in the stability domain to achieve mixed $_2/_\infty$ optimal control. A similar work was proposed in Shinn-Jang Ho et al. [8] by using the intelligent genetic algorithm to solve the mixed $_2/_\infty$ optimal control problem.

The techniques mentioned above are based on the concept of $_\infty$ optimal control which two appropriate weights for both the uncertainty of the model and the performance are essentially chosen. A difficulty with the $_\infty$ optimal control approach is that the appropriate selection of close-loop objectives and weights is not straightforward. In robust control, $_\infty$ loop shaping which is a simple and efficient technique for designing a robust controller can be alternatively used to design the robust controller for the system. Uncertainties in this approach are modeled as normalized co-prime factors; this uncertainty model does not represent actual physical uncertainty, which usually is unknown in real problems. This technique requires only two specified weights, pre-compensator and post-compensator, for shaping the nominal plant so that the desired open loop shape is achieved. Fortunately, the selection of such weights is based on the concept of classical loop shaping which is a well known technique in controller design. By the reasons mentioned above, this technique is simpler and more intuitive than other robust control techniques. However, the controller designed by $_\infty$ loop shaping is still complicated and has high order. To overcome this problem, in this paper, we propose a fixed-structure $_\infty$ loop shaping control to design a robust controller for a buck-boost converter. In the proposed technique, the controller structure is first specified and the genetic algorithm is then used to evaluate the control's parameters. Simulation and experimental results show the advantages of simple structure, lower order and robustness of the proposed controller.

The remainder of this paper is organized as follows. Converter dynamics are described in Section 14.2. H_∞ loop shaping and the proposed technique are discussed in Section 14.3. Section 14.4 demonstrates the design example and results. Finally, Section 14.5 concludes the paper with some final remarks.

14.2 Converter Modeling

A typical circuit of buck-boost converter with current mode control is shown in Fig. 14.1. The dynamic model of this converter from the current reference (i_r) to output voltage (v_o) is given by Ridley [2] and Kassakian [3].

$$\frac{dv_o}{di_r} = R_L \frac{V_i}{V_i + 2V_o} \frac{\left(1 - \frac{s \cdot L}{R_L} \cdot \frac{V_o}{V_i} \cdot \frac{V_o - V_i}{V_o}\right)}{\left(1 + s \cdot C \cdot R_L \cdot \frac{V_o + V_i}{2V_o + V_i}\right)} \tag{14.1}$$

where R_L is the nominal load resistant, V_o is the nominal output voltage, V_i is the nominal input voltage, L is the inductance of an inductor used in the circuit, C is the capacitance, f_{sw} is the switching frequency. The accuracy of this model has been proved to be accepted, at least in frequency of interest in this application.

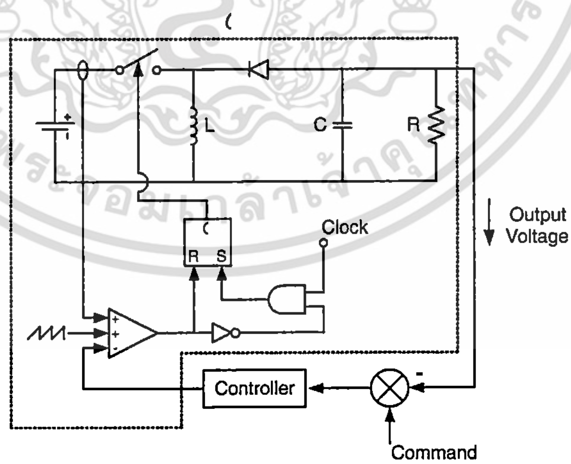

Fig. 14.1 Buck-boost converter with current mode control

14.3 7 $_\infty$ Loop Shaping Control and Proposed Technique

This section illustrates the concepts of the standard $_\infty$ loop shaping control and the proposed technique. Consider the system described by the block diagram (Fig. 14.2), where the plant (and the controller / are real rational and proper. y is the output, u is the control input, v is the vector signal including noises, disturbances, and reference signals, and z is the vector signal including all controlled signals and tracking errors. The $_\infty$ optimal control problem is to find admission controller / (z) such that $||7_{zv}||_\infty$ is minimized, where $||7_{zv}||_\infty$ is the maximum norm of the transfer function from v tc z, and the admission controller is the controller that internally stabilizes the system [9].

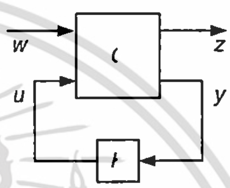

Fig. 14.2 General block diagram in robust control problem

14.3.1 Standard 7 $_\infty$ Loop Shaping

$_\infty$ loop shaping control [9] is an efficient method to design a robust controller. This approach requires only a desired open loop shape in frequency domain. Two weighting functions, $\text{\textbackslash}_1$ (pre-compensator) and $\text{\textbackslash}_2$ (post-compensator), are specified to shape the original plant (. In this approach, the shaped plant is formulated as normalized coprime factor, which separates the plant $(_s$ into normalized nominator $/_s$ and denominator $/\!l_s$ factors. If the shaped plant $(_s = \backslash_1 G \backslash_2 = /_s /\!l_s^{-1}$, then a perturbed plant can be written as

$$(_{\angle} = (/_s + \angle_{/_s})(/\!l_s + \angle_{/\!l_s})^{-1} \tag{14.2}$$

Where Δ_{Ns} and Δ_{Ms} are stable, unknown representing the uncertainty satisfying $||\Delta_{Ns}, \Delta_{Ms}||_\infty \leq \varepsilon$, ε is the uncertainty boundary, called stability margin.

According to the standard procedure of $_\infty$ loop shaping, the following steps can be applied to design the $_\infty$ loop shaping controller.

Step 1 Shape the singular values of the nominal plant $(_c$ by using a pre-compensator $\backslash_1$ and/or a post-compensator $\backslash_2$ to get the desired loop shape. $\backslash_2$ can be chosen as an identity matrix, since we can neglect the sensor noise effect when the use of good sensor is assumed [10]. Weight selection is very important for the design. There are some guidelines for the weight selection in Siguard Skogestad and Ian Postlethwaite [11]. In SISO system, the weighting functions $\backslash_1$ and $\backslash_2$ can be chosen as

$$W_1 = K_w \frac{s+a}{s+b} \quad \text{and} \quad W_2 = \frac{c}{s+c} \tag{14.3}$$

where K_w, a, b and c are positive values.

Step 2 Minimize ∞ – norm of the transfer matrix T_{zw} over all stabilizing controllers K to obtain an optimal cost γ_{opt}, as

$$\gamma_{opt} = \varepsilon_{opt}^{-1} = \inf_{stabK} \left\| \begin{bmatrix} I \\ K \end{bmatrix} (I + G_s K)^{-1} M_s^{-1} \right\|_\infty \tag{14.4}$$

To determine ε_{opt}, there is a unique method explained in Siguard Skogestad and Ian Postlethwaite [11]. $\varepsilon_{opt} << 1$ indicates that W_1 or W_2 designed in step 1 are incompatible with robust stability requirement. If ε_{opt} is not satisfied ($\varepsilon_{opt} << 1$), then return to step 1, adjust W_1.

Step 3 Select $\varepsilon < \varepsilon_{opt}$ and then synthesize a controller K_∞ that satisfies

$$\|T_{zw}\|_\infty = \left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (I + G_s K_\infty)^{-1} M_s^{-1} \right\|_\infty \le \varepsilon^{-1} \tag{14.5}$$

Controller K_∞ is obtained by solving the optimal control problem. More detail is available in Siguard Skogestad and Ian Postlethwaite [11].

Step 4 Final controller (K) follows

$$K = W_1 K_\infty W_2 \tag{14.6}$$

14.3.2 Genetic Algorithm Based Fixed-Structure H_∞ Loop Shaping Optimization

Practical implementation of the controller derived from H_∞ loop shaping method is difficult because the order of the controller is quite high. In this paper, the genetic searching algorithm is adopted to solve this problem. Although the proposed controller is structured, it still retains the entire robustness and performance guarantee as long as a satisfactory uncertainty boundary ε is achieved. The proposed algorithm is explained as following.

Assume that the predefined structure controller $K(p)$ has a satisfied parameters p. Based on the concept of H_∞ loop shaping, optimization goal is to find parameters p in controller $K(p)$ that minimize infinity norm $\|T_{zw}\|_\infty$. In the proposed technique, the final controller K is defined as

$$K = K(p) W_2 \tag{14.7}$$

Assuming that W_1 is invertible, from (14.6) then it is obtained that

$$K_\infty = W_1^{-1} K(p) \tag{14.8}$$

In many cases, the weight W_2 is selected as identity matrix I. However, if W_2 is a transfer function matrix, then the final controller is the controller $K(p)$ in series with the weight W_2. By Substitution of (14.8) into (14.5), then the ∞-norm of the transfer function matrix from disturbances to states, $\|T_{zw}\|_\infty$, which is subjected to be minimized can be written as

$$J_{cost} = \gamma = \|T_{zw}\|_\infty = \left\| \begin{bmatrix} I \\ W_1^{-1}K(p) \end{bmatrix} (I + G_s W_1^{-1} K(p))^{-1} M_s^{-1} \right\|_\infty \quad (14.9)$$

In this paper, GA is adopted to find the optimal control parameters p^* in the stabilizing controller *K(p)* such that the $\|T_{zw}\|_\infty$ is minimized.

14.3.2.1 Genetic Algorithms

GA is well known as a biologically inspired class of algorithms that can be applied to any nonlinear optimization problem. This algorithm applies the concept of chromosomes, and the operations of crossover, mutation and reproduction. At each step, called generation, fitness values of all chromosomes in population are calculated. Chromosome, which has the maximum fitness value (minimum cost value), is kept as a solution in the current generation and passed to the next generation. The new population of the next generation is obtained by performing the genetic operators such as crossover, mutation, and reproduction. Crossover randomly selects a site along the length of two chromosomes, and then splits the two chromosomes into two pieces by breaking them at the crossover site. The new chromosomes are then formed by matching the headpiece of one chromosome with the tailpiece of the other. Mutation operation forms a new chromosome by randomly changing value of a single bit in the chromosome. Reproduction operation forms a new chromosome by just copying the old chromosome. Chromosome selection in genetic algorithm depends on the fitness value; high fitness value means high chance to be selected. Operation type selection; mutation, reproduction, or crossover, depends on the pre-specified operation's probability. Chromosome in genetic population is coded as binary number. However, for the real number problem, decoding binary number to floating number is applied [12]. Our proposed algorithm is summarized as

Step 1 Shape the singular values of the nominal plant G by W_1 and W_2. Then evaluate the ε_{opt} using (14.4). If $\varepsilon_{opt} < 0.25$, then go to step 1 to adjust the weight W_1.

Step 2 Select a controller structure *K(p)* and initialize several sets of parameters p as population in the 1st generation. Define the genetic parameters such as initial population size, crossover and mutation probability, maximum generation, etc.

Step 3 Evaluate the cost function J_{cost} of each chromosome using (14.9). Assign $J_{cost} = 100$, or large number if *K(p)* does not meet the constraints in our optimization problem. The fitness value is assigned as $1/J_{cost}$. Select the chromosome with minimum cost function as a solution in the current generation. For the first generation, Gen = 1.

Step 4 Increment the generation for a step.

Step 5 While the current generation is less than the maximum generation, create a new population using genetic operators and go to step 3. If the current generation is the maximum generation, then stop.

Step 6 Check performances in both frequency and time domains. If the performance is not satisfied, such as too low ε (too low fitness function), then go to step 3 to change the control structure. Low ε indicates that the selected control structure is not suitable for the problem.

14.4 Simulation and Experimental Results

In this paper, a buck-boost converter designed for a photovoltaic system is studied. Converter's parameters and considered variation ranges used in this paper are given in Table 14.1.

By (14.1), the nominal transfer function is found to be

$$(= \frac{-0.0042s + 480}{0.7896s + 72} \tag{14.10}$$

Both $_\infty$ loop shaping control and our proposed technique are applied to this converter. Firstly, we design a controller by the conventional $_\infty$ loop shaping procedure. Based on the concept of $_\infty$ loop shaping, Ɩ $_1$ and Ɩ $_2$ can be selected as

$$Ɩ_1 = 30\frac{(s + 26.7)}{(s + 0.001)},\ Ɩ_2 = \frac{100000}{s + 100000} \tag{14.11}$$

Figure 14.4(a) shows the plot of open loop shape of nominal plant and shaped plant. As seen in this figure, the bandwidth of the nominal plant is about 600 rad/sec. With these weighting functions, bandwidth of the desired control system is increased to 20,000 rad/sec. Significant improvement in terms of performances and robustness is carried out by these weighting functions. The shaped plant is written as

$$(_s = Ɩ_1 G Ɩ_2 = 30\frac{(s + 26.7)}{(s + 0.001)}\frac{(-0.0042s + 480)}{(0.7896s + 72)}\frac{(100000)}{(s + 100000)} \tag{14.12}$$

Table 14.1 Converter's parameters and considered variation ranges

Parameter	Name	Nominal value
I_l	Load resistant	40 Ω
Ɩ $_c$	Output voltage	30 V
Ɩ $_i$	Input voltage	12 V
l	Inductance	100 μ I
(	Capacitor	470 μ I
f_s	Switching frequency	100 kHz

By applying the H_∞ loop shaping method, the optimal stability margin (ε_{opt}) is founded at 0.612 ($\gamma_{opt} = 1.6338$). This value indicates that the selected weighting function is compatible with the robust stability requirement. The $\varepsilon = 0.590$ ($\gamma = 1.6949$), which is less than the optimal stability margin, is chosen to synthesize the controller. Based on the conventional technique in Section 14.3, the conventional H_∞ loop shaping controller is synthesized as following

$$K(s) = W_1 K_\infty W_2 = 30\frac{(s+26.7)}{(s+0.001)} \frac{(261841)(s+1.002\times10^5)(s+26.9)}{(s^2+3.265\times10^5 s+3.608\times10^{10})(s+26.7)} \times \frac{(100000)}{(s+100000)} \tag{14.13}$$

As shown in (14.13), the controller is 5[th] order controller resulting in a complicated structure. Next, PI controller is investigated as a fixed-structure controller. The controller structure is expressed in (14.14). K_p and K_i are parameters that will be evaluated.

$$K(p) = K_p + \frac{K_i}{s} \tag{14.14}$$

The controller parameters, their ranges, and genetic algorithms parameters are selected as follows: $K_p \in [0,200]$, $K_i \in [0,1000]$, population size = 100, crossover probability = 0.7, mutation probability = 0.25, and maximum generation = 30. An optimal solution is obtained after 18 generations. The optimal solution is shown in (14.15), which has stability margin (ε) of 0.586 ($\gamma = 1.7064$).

$$K(p)^* = 21.84 + \frac{597.6}{s} \tag{14.15}$$

The final controller (K) is shown in (14.16).

$$K = \left(21.84 + \frac{597.6}{s}\right)\left(\frac{100000}{s+100000}\right) \tag{14.16}$$

Figure 14.3 shows plots of convergence of cost function J_{cost} versus generations by genetic algorithm. As seen in this figure, the optimal fixed-structure controller provides the satisfied stability margin at 0.586 ($\gamma = 1.7064$). The open loop bode diagrams of the nominal and shaped plants are shown in Fig. 14.4(a). As shown in this figure, at low frequency, the open loop gain of shaped plant is much larger than that of the nominal plant. This makes the system good in term of performance tracking and disturbance rejection. Open loop bode diagrams are plotted in Fig. 14.4(b) to verify the proposed algorithm. It is clearly shown that the loop shapes of H_∞ control and proposed PI controller are close to the desired loop shape. Figure 14.4(c) shows the step responses of the optimal solutions from the proposed robust PI and the conventional H_∞ controllers. As shown in this figure, the settling time of all responses is about 500 μ sec.

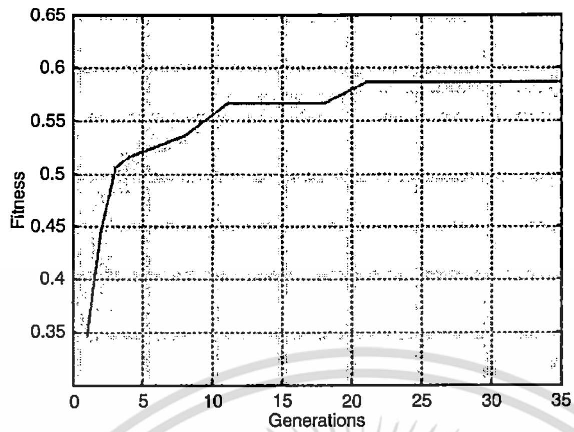

Fig. 14.3 Fitness functions versus iterations in genetic algorithm

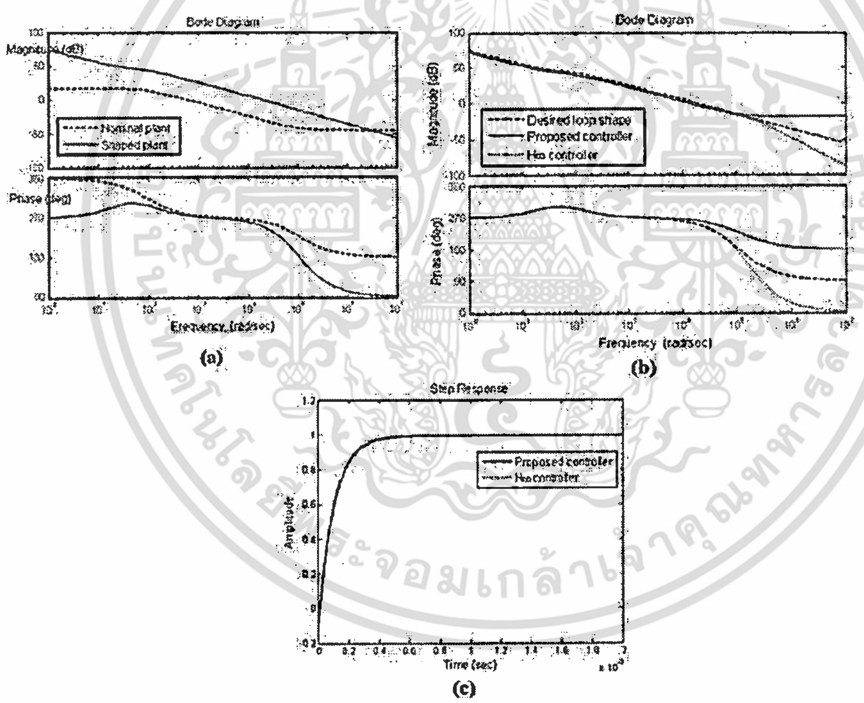

Fig. 14.4 (a) Bode plots of the nominal plant and the shaped plant (*desired loop shape*) (b) The desired loop shape and the loop shape by the conventional H_∞ loop shaping and the proposed PI, (c) Step responses by the proposed PI and H_∞ loop shaping controllers

In addition, in this paper, we apply the conventional PI controller based on the ISE method. In this method, the controller parameter is tuned in such a way that the integral of square error between output and desired response is minimized. However, to prevent the oscillations in the response, ISE with the model reference can be applied [13]. In this paper, we adopted the ISE with model reference to design a PI controller to make the settling time close to 500 μ sec. The resulting controller is,

$$I_{ISE} = 19 + \frac{2800}{s} \qquad (14.17)$$

The step responses of proposed and $_\infty$ controllers in the nominal plant and perturbed plant are shown in Fig. 14.5(a) and (b), respectively. As shown in the figures, the responses in perturbed plant are almost the same as the responses in the nominal plant with some different in the setting time. The results show that the designed system from the proposed controller and $_\infty$ loop shaping has a good performance and robustness. To verify the robust performance, we change the converter's parameters as: $I_l = 10\ \Omega$, $\backslash_i = 10.8$ V, $l = 130$ μ H and $(= 2200$ μ F. The designed controllers in (14.16) and (14.17) are adopted to control the perturbed plant. Obviously, this condition (increase L and (and decrease the load resistance and input voltage) is worse than the nominal condition, because in this case the gain and phase of the plant are decreased in the crossover region.

Some experiments are performed to verify the effectiveness of the proposed controller. The nominal values in Table 14.1 are used to design a buck-boost converter with current mode control. A proposed robust PI controller in (14.16) and PI controller tuned by ISE method in (14.17) are used to control the converter. As seen in Figs. 14.5(a) and 14.6, the response of experimental result is almost the same as that of the simulation result.

To verify the robust performance of the system, an experiment is performed. The component values and operating point of the converter are changed to:

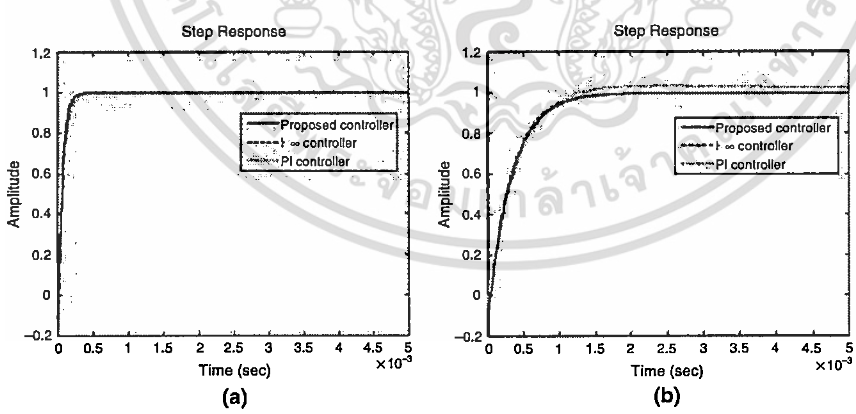

Fig. 14.5 (a) Step responses in the nominal plant. (b) Step responses in the perturbed plant

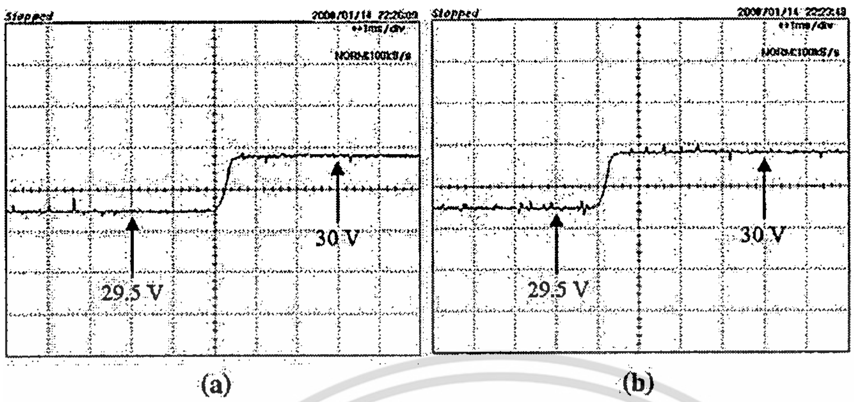

Fig. 14.6 Step responses in nominal condition. (a) Proposed PI controller. (b) PI tuned by ISE method

$R_L = 10\ \Omega$, $V_i = 10.8$ V, $L = 130\ \mu$H and $C = 2200\ \mu$F. The performance is verified by using the step response. As shown in Fig. 14.7, the step response of the proposed controller is almost the same as the response in nominal conditions while the step response of the PI controller tuned by ISE method has an overshoot when the system parameters change. This can be verified that the robust performance of the proposed technique is better than that of PI controller by ISE method.

To verify the robust against the sudden change of load, an experiment were performed. As shown in Fig. 14.8, when the load is abruptly changed, the proposed controller can maintain the desired voltage.

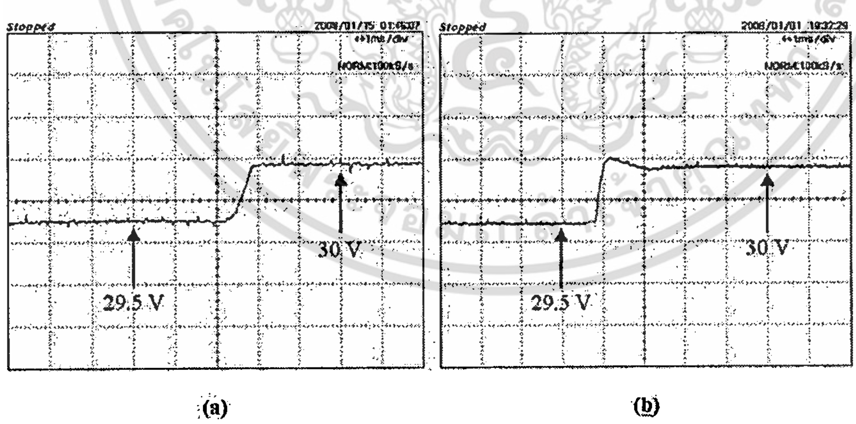

Fig. 14.7 Step response in the closed loop in perturbed conditions. (a) Proposed PI controller. (b) PI tuned by ISE method

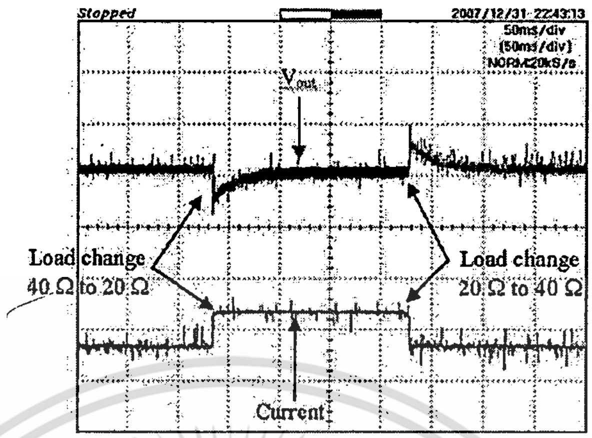

Fig. 14.8 Transient response of propose controller when the load change 40–20 Ω

14.5 Conclusion

Both $_{\infty}$ loop shaping and *GA based fixed-structure* $_{\infty}$ *loop shaping control*, are applicable in designing a robust controller for a current mode buck-boost converter. However, the proposed approach significantly improves the controller design in practical control viewpoint by simplifying the controller structure, reducing the controller order and retaining the robust performance. Structure of controller in the proposed technique is selectable. This is desirable, especially in the DC–DC converter which analog circuit is normally used to design the controller. In conclusion, by combining of these two approaches, genetic algorithms and $_{\infty}$ loop shaping; fixed-structure controller design can be achieved. Implementation in buck-boost converter assures that the proposed technique is valid and flexible.

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Genetic Algorithm based Fixed-Structure H_∞ Loop Shaping Control of a Buck-Boost Converter

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***Abstract* –H_∞ loop shaping is a feasible method for designing robust controller; however, the controller designed by this ethod is complicated and has high order. It is not easy to plement this controller in practice. To overcome this problem, e propose an algorithm, *GA based fixed-structure H_∞ loop aping control*, to design a robust controller. In the proposed chnique, genetic algorithm is used to solve the H_∞ loop shaping sign problem under a structure specified controller. To mpare performance, conventional H_∞ loop shaping, proposed bust controller and conventional ISE method are investigated. sults of simulation demonstrate the advantages of a simple ructure and robustness against plant perturbations and sturbances of the proposed controller. In this paper, the oposed technique is adopted to design a robust controller of a CMC buck-boost converter. Experiments are performed to rify the effectiveness of the proposed technique.**

***Index Terms* - H_∞ loop shaping, Buck-Boost converter, netic algorithm**

I. INTRODUCTION

DC-DC converters have been widely used in computer rdware and industrial applications. Controlling of these nverters is a challenging filed because of their intrinsic ture of nonlinear, time-variant systems [1]. In previous search works, the linear models of these converters were rived by using linearization method [2-3]. Some linear ntrol techniques were applied to these converters based on e linear models [1, 4-5]. NAIM, R., *et.al.*[4], applied the H_∞ ntrol to a boost converter. Three types of controller; voltage ode, feed-forward and current mode control were vestigated and compared the performance. G.C. Ioannidis d S.N. Manias [5] applied the H_∞ loop shaping control for a ck converter. In their paper, the μ-analysis was used to amine the robust features of the designed controllers. mone Buso [1] adopted the robust μ-synthesis to design a bust voltage controller for a buck-boost converter with rrent mode control. The parameter variations in the nverter's transfer function were described in term of rturbations of linear fraction transformations (LFT) class.

In DC-DC converters, uncertainties from the operating int variations and components' tolerances strongly affect to e dynamic of converters. These uncertainties can be nsidered in the controller design by applying the robust ntrol scheme. In robust control, H_∞ optimal control is a powerful technique to design a robust controller for system with uncertainties and disturbances. However, the controller designed by conventional H_∞ optimal control is complicated controller and has high order. It is difficult to implement the controller in practice. To overcome this problem, the approaches for designing a robust control for structure specified controller were proposed in [6-8]. In [6], a robust H_∞ optimal control problem with structure specified controller was solved by genetic algorithm (GA). Bor-Sen.Chen. *et. al.*[7], proposed a PID design algorithm for mixed H_2/H_∞ control. In their paper, PID controller parameters were tuned in the stability domain to achieve mixed H_2/H_∞ optimal control. Somyot and Manukid [8] proposed a genetic algorithm to solve the H_∞ loop shaping control design problem under the structure specified controller and applied their controller to control a servo pneumatic system. A simple structure and robust controller was achieved by their proposed technique.

One of the advantages of H_∞ loop control shaping control is that the classical loop shaping design can be applied. This approach involves the robust stabilization to additive perturbations of normalized co-prime factors of a shaped plant. Uncertainties in this approach are modelled as co-prime factor uncertainty of the shaped plant. However, the controller designed by this approach is still complicated. In this paper, we proposed a fixed-structure H_∞ loop shaping control to design a robust controller for a Buck-Boost converter. Our approach is based on the concept of H_∞ loop shaping control. In the design, we specify the controller structure and then evaluate the control's parameters by GA. In the future work, we will adopt the proposed controller to control the dc servo system of the visual inspection in HDD (Hard-Disk-Drive) industry.

The remainder of this paper is organized as follows. Converter dynamics model is described in section II. H_∞ loop shaping and the proposed technique are discussed in section III. Section IV demonstrates the design example and results. Finally, section V concludes the paper with some final remarks.

II. CONVERTER MODELING

A typical circuit of Buck-Boost converter with current mode control is shown in Fig. 1.

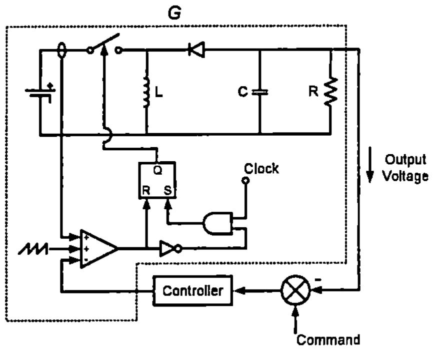


Fig. 1. Buck-Boost converter with current mode control.

The dynamic model of this converter from the current rence to output voltage is given as follow [2-3]:

$$\frac{du_o}{di_r} = R_L \frac{V_i}{V_i + 2V_o} \frac{(1 - \frac{s \cdot L}{R_L} \cdot \frac{V_o}{V_i} \cdot \frac{V_o + V_i}{V_o})}{(1 + s \cdot C \cdot R_L \cdot \frac{V_o + V_i}{2V_o + V_i})} \quad (1)$$

The accuracy of this model has been proved to be epted, at least in frequency of interest in this application [2-

I. H_∞ Loop Shaping Control and Propose Technique

This section illustrates the concept of the standard H_∞ loop ping control and the proposed technique.

tandard H_∞ Loop Shaping Control

H_∞ loop shaping control [12] is an efficient method for gning a robust controller. This approach requires only a red open loop shape in frequency domain. Two weighting ctions, W_1 (pre-compensator) and W_2 (post-compensator), specified to shape the original plant G_o such that the cifications in frequency domain are achieved. In this roach, the shaped plant is formulated as normalized co-ne factor, which separates the plant G_s into normalized inator N_s and denominator M_s factors. Fig. 2 shows the co-ne perturbed plant and robust stabilization used in this roach.

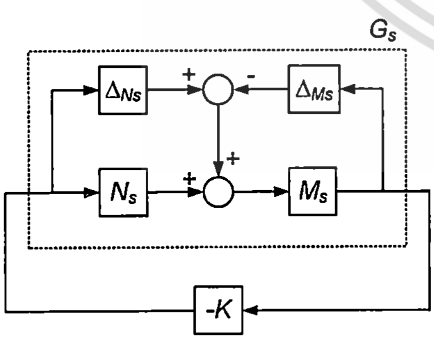


Fig. 2. Co-prime factor robust stabilization problem.

If the shaped plant $G_s = W_1 G_0 W_2 = N_s M_s^{-1}$, then a turbed plant can be written as [12]

$$G_\Delta = (N_s + \Delta_{N_s})(M_s + \Delta_{M_s})^{-1} \quad (2)$$

Where Δ_{Ns} and Δ_{Ms} are stable, unknown representing the uncertainty satisfying $\|\Delta_{Ns}, \Delta_{Ms}\| \le \varepsilon$,

ε is the uncertainty boundary, called stability margin.

According to the standard procedure of H_∞ loop shaping, the following steps can be applied to design the H_∞ loop shaping controller.

Step 1 Shape the singular values of the nominal plant G_o by a pre-compensator W_1 and/or a post-compensator W_2 to get the desired loop shape. W_2 can be chosen as an identity matrix, since we can neglect the sensor noise effect when the using of good sensor is assumed [13].

Step 2 Minimize ∞-norm of the transfer matrix T_{zw} over all stabilizing controllers K , to obtain an optimal cost γ_{opt} , as [13]

$$\gamma_{opt} = \varepsilon_{opt}^{-1} = \inf_{stabK} \left\| \begin{bmatrix} I \\ K \end{bmatrix} (I + G_s K)^{-1} M_s^{-1} \right\|_\infty \quad (3)$$

To determine ε_{opt} , there is a unique method explained in [14]. $\varepsilon_{opt} << 1$ indicates that W_1 or W_2 designed in step 1 are incompatible with robust stability requirement. If ε_{opt} is not satisfied ($\varepsilon_{opt} << 1$) , then return to step 1 and adjust W_1 .

Step 3 Select $\varepsilon < \varepsilon_{opt}$ and then synthesize a controller K_∞ by solving the following inequality.

$$\|T_{zw}\|_\infty = \left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (I + G_s K_\infty)^{-1} M_s^{-1} \right\|_\infty \le \varepsilon^{-1} \quad (4)$$

The method used for synthesizing K_∞ can be seen in [14].

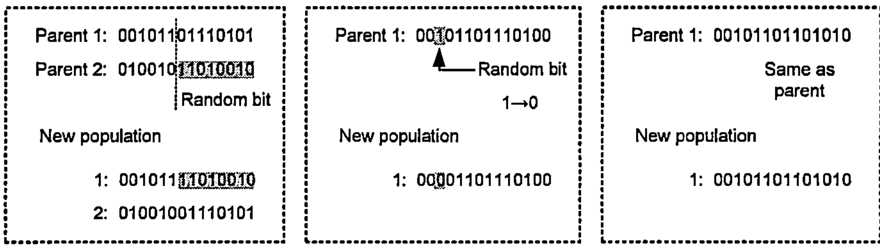
Step 4 Find the final controller (K) as follow:

$$K = W_1 K_\infty W_2 \quad (5)$$

B. Genetic Algorithm based Fixed-Structure H_∞ Loop Shaping Optimization

The controller which is derived from H_∞ loop shaping method is normally complicated controller and has a high-order. It is difficult to apply this controller in real works. Nowadays, the fixed-structure robust controller becomes an interesting research area because of their advantages of simple structure and acceptable controller's order. In this paper, the genetic searching algorithm is adopted to solve this problem. Although the proposed controller is structured, it still retains the entire robustness and performance guarantee as long as a satisfactory uncertainty boundary ε is achieved. The proposed algorithm is explained as following.

Assume that the predefined structure controller $K(p)$ has a satisfied parameters p. Based on the concept of H_∞ loop shaping, optimization goal is to find parameters p in controller



(a) Crossover (b) Mutation (c) Reproduction

Fig. 3. Genetic Operations (a) Crossover (b) Mutation and (c) Reproduction.

(p) that minimize infinity norm $\|T_{zw}\|_\infty$. In the proposed echnique, the final controller K is the controller $K(p)$ in eries with the weight W_2, defined as

$$K = K(p)W_2 \quad (6)$$

ssume that W_1 is invertible, form (5) then it can be btained that

$$K_\infty = W_1^{-1}K(p) \quad (7)$$

By Substitution of (7) into (4), the ∞-norm of the ansfer function matrix from disturbances to states , $\|T_{zw}\|_\infty$, hich is subjected to be minimized can be written as

$$J_{cost} = \gamma = \|T_{zw}\|_\infty = \left\| \begin{bmatrix} I \\ W_1^{-1}K(p) \end{bmatrix} (I + G_s W_1^{-1} K(p))^{-1} M_s^{-1} \right\|_\infty \quad \ldots(8)$$

In this paper, GA is adopted to find the optimal control arameters p^* in the stabilizing controller $K(p)$ such that the $\|T_{zw}\|_\infty$ is minimized. The optimization problem can be ritten as

$$\text{Minimize} \left\| \begin{bmatrix} I \\ W_1^{-1}K(p) \end{bmatrix} (I + G_s W_1^{-1} K(p))^{-1} M_s^{-1} \right\|_\infty$$

ubject to

$$p_{i,\min} < p_i < p_{i,\max} \ ,$$

here $p_{i,min}$ and $p_{i,max}$ are the lower bound and upper bounds f the parameter p_i, respectively. Some useful methods for electing these bounds can be seen in [6-7].

enetic Algorithms

Our proposed technique adopts GA to solve the ptimization problem in (8). GA is well known as a ologically inspired class of algorithms that can be applied any nonlinear optimization problem. This algorithm pplies the concept of chromosomes, and the operations of rossover, mutation and reproduction. At each step, called eneration, fitness values of all chromosomes in population e calculated. Chromosome, which has the maximum tness value (minimum cost value), is kept as a solution in e current generation and passed to the next generation. The ew population of the next generation is obtained by performing the genetic operators such as crossover, mutation, and reproduction. Crossover randomly selects a site along the length of two chromosomes, and then splits the two chromosomes into two pieces by breaking them at the crossover site. The new chromosomes are then formed by matching the headpiece of one chromosome with the tailpiece of the other. Mutation operation forms a new chromosome by randomly changing value of a single bit in the chromosome. Reproduction operation forms a new chromosome by just copying the old chromosome. Chromosome selection in genetic algorithm depends on the fitness value. High fitness value means high chance to be selected. Operation type selection; mutation, reproduction, or crossover, depends on the pre-specified operation's probability.

Chromosome in genetic population is generally coded as binary number; however, for the real number problem, decoding binary number to floating number can be applied [15]. Basic operations; crossover, mutation, and reproduction, are described in Fig. 3.

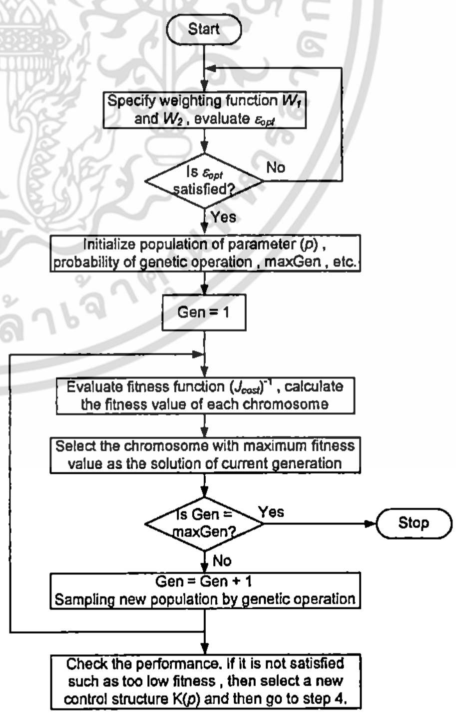


Fig. 4. Flow chart of the proposed design procedure.

Dur proposed algorithm is summarized as:

;tep 1 Specify the weight W_1 and W_2. Shape the singular ralues of the nominal plant G_o.

;tep 2 Evaluate the ε_{opt} using (3). If $\varepsilon_{opt} << 1$, then go to tep 1 to adjust the weight W_1.

;tep 3 Select a controller structure *K(p)* and initialize everal sets of parameters *p* as population in the 1^{st} eneration. Define the genetic parameters such as initial opulation size, crossover and mutation probability, naximum generation, etc.

;tep 4 Evaluate the cost function J_{cost} of each chromosome ısing (8). Assign J_{cost} = 100, or other large number if *K(p)* loes not stabilize the system. The fitness value is assigned s $1/J_{cost}$. Select the chromosome with minimum cost unction as a solution in the current generation. For the first eneration, Gen = 1.

;tep 5 Increment the generation for a step.

;tep 6 While the current generation is less than the naximum generation, create a new population using genetic perators and go to step 4. If the current generation is the naximum generation, then stop.

;tep 7 Check performances in both frequency and time lomains. If the performance is not satisfied, such as too low : (too low fitness function), then go to step 3 to change the ontrol structure. Low ε indicates that the selected control tructure is not suitable for the problem. Fig. 4 shows the lowchart of the proposed technique mentioned above.

IV. Simulation And Experimental Results

In this paper, a buck-boost converter is designed for mplementing as the plant. Converter's parameters and onsidered variation ranges used in this paper are given in Cable I.

TABLE I
CONVERTER'S PARAMETERS AND CONSIDERED VARIATION RANGES.

Parameter	Name	Nominal Value
R_L	Load Resistant	40 Ω
V_o	Output Voltage	30 V
V_i	Input Voltage	12 V
L	Inductance	100 µH
C	Capacitor	470 µF
f_{sw}	Switching frequency	100 kHz

3y (1), the nominal transfer function is found to be

$$G_o = \frac{(-0.0042s + 480)}{(0.7896s + 72)} \quad (9)$$

n this case, W_1 and W_2 can be selected as

$$W_1 = 30\frac{(s + 26.7)}{(s + 0.001)} \quad (10)$$

$$W_2 = \frac{100000}{s + 100000} \quad (11)$$

The selected weights make the system good in terms of high bandwidth and large gain the low frequency range. Both H_∞ loop shaping control and our proposed technique are applied to this converter. Firstly, we design a controller by the conventional H_∞ loop shaping procedure. W_2 is chosen as 1 since we neglect the sensor noise effect when the use of good sensor is assumed. The shaped plant can be written as:

$$G_s = W_1 G W_2 = L = 30\frac{(s+26.7)}{(s+0.001)}\frac{(-0.0042s + 480)}{(0.7896s + 72)}\frac{(100000)}{(s+100000)} \quad ...(12)$$

By applying the H_∞ loop shaping method, the optimal stability margin (ε_{opt}) is found at 0.612 (γ_{opt} = 1.6338). The ε = 0.590 (γ = 1.6949) is selected to synthesis the controller. By this approach, we obtain the conventional H_∞ loop shaping controller as following

$$K(s) = W_1 K_\infty W_2$$
$$= 30\frac{(s+26.7)}{(s+0.001)}\frac{(261841)(s+1.002\times10^5)(s+26.9)}{(s^2+3.265\times10^5 s+3.608\times10^{10})(s+26.7)}\frac{(100000)}{(s+100000)} \quad ...(13)$$

As shown in (13), the controller is 5^{th} order and has a complicated structure. Next, PI controller structure is selected in the proposed technique. The controller structure is expressed in (14). K_p and K_i are parameters that will be evaluated.

$$K(p) = K_p + \frac{K_i}{s} \quad (14)$$

Select the controller parameters, their ranges, and genetic algorithms parameters as following: $K_p \in [0,200]$, $K_i \in [0,1000]$, population size = 100, crossover probability = 0.7, mutation probability = 0.25, and maximum generation = 35. An optimal solution is obtained after running the GA for 21 generations. The optimal solution is shown in (15), which has stability margin (ε) of 0.5918 (γ = 1.689).

$$K(p)^* = 21.84 + \frac{597.6}{s} \quad (15)$$

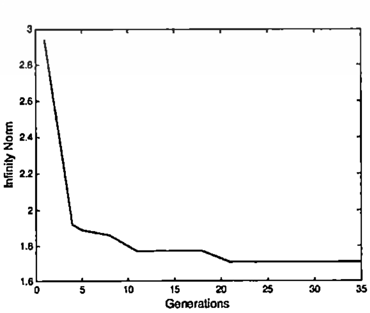


Fig. 5. Cost functions J_{cost} versus iteration in genetic algorithm.

The final controller (K) is shown in (16).

$$K=\left(21.84+\frac{597.6}{s}\right)\left(\frac{100000}{s+100000}\right) \tag{16}$$

Fig. 5 shows the plots of convergence of cost function $_{cost}$ versus generations by genetic algorithm. Optimal fixed-tructure controller provides the satisfied stability margin at .586 (γ = 1.7064). Next, a PI controller tuned by ISE Integral of Square Error) method [16] with settling time lose to that of the proposed controller (approximately 400 sec) is designed.

$$K_{ISE}=19+\frac{2800}{s} \tag{17}$$

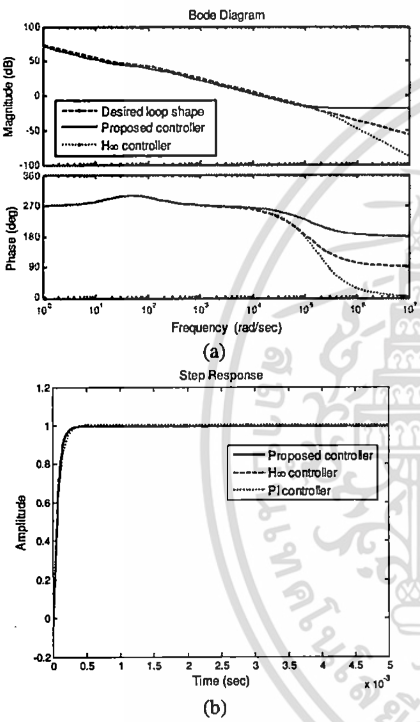


Fig. 6. (a) The desired loop shape and the loop shape by the conventional H_∞ loop shaping and the proposed controller. (b) Step responses of the proposed controller, H_∞ controller and PI controller.

)pen loop bode diagrams of all controllers are plotted in 'ig. 6 (a) to verify the proposed algorithm. It is clearly hown that the loop shapes of H_∞ controller and proposed ontroller are close to the desired loop shape. Fig. 6 (b) hows the step responses of the optimal solutions from the roposed controller, the conventional H_∞ and PI controllers. ıs shown in this figure, the settling time of all step esponses is about 300-400 μsec. To verify the robust erformance, we change the converter's parameters as: R_L = 0 Ω, V_i = 10.8 V, L = 130 μH and C = 2200 μF. This case ıay be occurred when the load is change, parameters are hanged and there are some capacitors at load connected in parallel with the converter. The designed controllers in (13), (16) and (17) are adopted to control this perturbed plant.

The step responses of all controllers are evaluated in this perturbed plant. As shown in Fig. 7, all of step responses are similar to the results at the nominal plant. However, there is a few overshoot in the response from conventional PI controller.

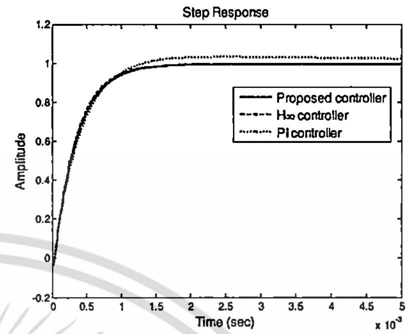


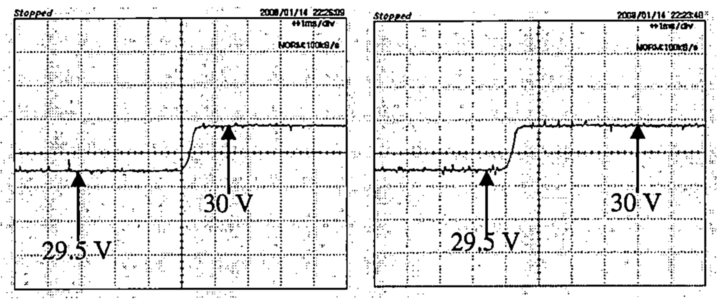
Fig. 7. Step responses in the perturbed plant. (R_L = 10 Ω , V_i = 10.8 V , L = 130 μH and C = 2200 μF).

Some experiments are performed to verify the effectiveness of our proposed controller. The nominal values in Table I are used to design a buck-boost converter. The step responses from the proposed controller in (16) and the PI controller tuned by ISE method in (17) are investigated. Fig. 8(a) shows the experimental results of step responses of the proposed controllers. The settling time of step responses is about 300-400 μsec which is almost the same as simulation results in Fig. 6(b).

To verify the robust performance of the system, some other experiments are performed. The component values and operating point of converter are changed to the perturbed plant. The performance is verified by using the step responses. As shown in Fig. 9(a), the step responses are almost the same as the responses in nominal condition. Experimental results verify that the proposed controller have good robust performance and can be applied for the buck-boost converter. Fig.9(b) show the step response of PI controller, overshoot occurs in the step response. As results indicated, the robust performance of the proposed controller is better than that of the conventional PI controller.

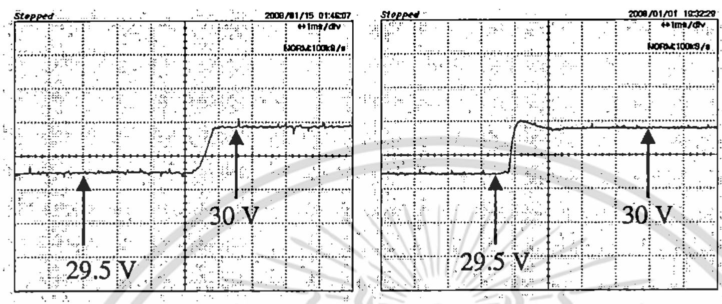
V. Conclusion

Both of H_∞ loop shaping and our proposed technique can be applied to design a robust controller for a buck-boost converter. However, the proposed approach significantly improves in practical control viewpoint by simplifying the controller structure, reducing the controller order and still retaining the robust performance.



(a) (b)

Fig.8. Step responses in the closed loop in nominal conditions for (a) Proposed controller (b) PI controller.



(a) (b)

Fig.9. Step responses in the closed loop in perturbed conditions for (a) Proposed controller (b) PI controller.

In conclusion, by combining of the approaches, genetic orithms, H_∞ loop shaping and robust loop shaping; fixed-icture controller design can be achieved. Implementation in :k-boost converter assures that the proposed technique is id and flexible. In the future work, the proposed controller l be used to control the position of camera in the visual pection system which is an important inspection in HDD nufacturing.

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PARTICLE SWARM OPTIMIZATION BASED FIXED-STRUCTURE H_∞ LOOP SHAPING CONTROL OF MIMO SYSTEM

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.BSTRACT

I_∞ loop shaping is a sensible method for designing a obust controller; however, the controller designed by onventional H_∞ loop shaping is complicated with a high rder. It is not easy to implement this controller in ractice. To overcome this problem, in this paper, a new esign technique of a fixed-structure robust controller for /IIMO system is proposed. The performance and robust tability conditions of the designed system satisfying the I_∞ loop shaping are formulated as the objective function 1 the optimization problem. Particle Swarm Optimization PSO) method is adopted to solve this problem and to chieve the control parameters of the proposed controller. 'he performance and robustness of the designed ontrollers, centralized and decentralized PID controllers, re investigated in a MIMO system (a chemical process) 1 comparison with the conventional H_∞ loop shaping ontrol. Simulation results show that the robustness and erformance of the proposed centralized controller are lmost identical to those of the controller designed by H_∞ oop shaping method. However, because of the omplicated controller in the conventional design, the roposed approach offers a significant improvement in ractical control viewpoints by simplifying the controller tructure, reducing the controller order and still retaining he robust performance. Simulation results also lemonstrate that the proposed approach is numerically fficient and leads to performance comparable to that of reviously published methods.

KEY WORDS

I_∞ loop shaping control, robust control, particle swarm ptimization, MIMO system, fixed-structure controller.

1. Introduction

n the past decades, many immense developments in obust control techniques have been proposed and the esults of those are applied to many control systems. As hown in previous research works, H_∞ optimal control is a owerful technique to design a robust controller for the ystem with uncertainties and disturbances. However, H_∞ robust controller is rarely applied in the industrial process because of its complicated structure. In industrial process control, structures such as lead-lag compensator and PID are widely used because their structure is simple, tuning parameters are fewer, and they are lower-order. Unfortunately, especially in MIMO system, tuning of controller parameters of such controllers for achieving a good performance and robustness is not easily carried out. To overcome this problem, several approaches to design a fixed-structure robust controller were proposed in [1-3, 5-7]. In [1], a robust H_∞ optimal control problem with structure specified controller was solved by using genetic algorithm (GA). As concluded in [1], genetic algorithm is a simple and efficient tool to design a structure specified H_∞ optimal controller. Bor-Sen.Chen. *et. al.*[2], proposed a PID design algorithm for mixed H_2/H_∞ control. In their paper, PID controller parameters were tuned in the stability domain to achieve mixed H_2/H_∞ optimal control. A similar work was also presented in [3]. The proposed techniques in [1-3] are based on the concept of mixed H_2/H_∞ optimal control which the structured uncertainty and performance weights must be specified in the design. However, especially in MIMO system, it is not easy to obtain the structured uncertainty weight in practice. Moreover, a difficulty with the H_∞ optimal control approach is that the appropriate selection of close-loop objectives and weights is not straightforward [4]. Alternatively, H_∞ loop shaping control was proposed [4] to design a robust controller based on unstructured uncertainty model. In the past decades, this approach has been successfully implemented in real applications. Uncertainties in this approach are modeled as the normalized left co-prime factor which is a useful model for designing a robust controller. Moreover, one of the advantages of H_∞ loop control shaping control is that the classical loop shaping design is incorporated in the design procedure. Thus, the well known concept in the classical loop shaping can be applied in this approach. However, the structure of controller designed by H_∞ loop shaping is also complicated with a high order. To overcome this problem, several approaches based on H_∞ loop shaping have been proposed to design a fixed-structure controller, such as a state-space approach by A. Umut. Genc in 2000

[5], non-smooth structured control design by Pierre Apkarian in 2005 [6], genetic algorithms based fixed-structure H_∞ loop shaping by Somyot and Manukid in 2004 [7], and etc. The methods used in [5-6] are based on the concept of local optimization techniques. Unfortunately, as shown in their results, the efficiency of final solution (optimal solution) is depended on the guess of initial solution at first step. Nevertheless, such techniques are based on the local optimization technique which has the problem of local minima. In [7], global optimization searching method was adopted to design the fixed-structure robust H_∞ loop shaping controller; however, the designed controllers in [7] were only implemented on a pneumatic servo system which is a SISO system. In this paper, the design of fixed-structure H_∞ loop shaping control for MIMO system is proposed. In the design, PSO is used to solve the optimization problem. Based on the concept of PSO, initial solution is not necessary for the proposed technique. To reduce the searching space in the proposed technique, the upper and lower bound values of solution are selected by observing the pre-compensator weight. In this paper, two fixed-structure controllers, centralized and decentralized PID controllers, are designed and implemented on a chemical process. As shown in the simulation results, the good performance and robustness are achieved by the designed controllers.

The remainder of this paper is organized as follows. Conventional H_∞ loop shaping and the proposed technique are discussed in section 2. PSO algorithm is also briefly described in this section. Section 3 demonstrates the design example and results. And, finally, in section 4 the paper is summarized with some final remarks.

2. H_∞ Loop Shaping Control and Proposed Technique

This section illustrates the concepts of the conventional H_∞ loop shaping control and the proposed technique.

2.1 Conventional H_∞ Loop Shaping

H_∞ loop shaping control is an efficient method to design a robust controller. This approach requires two weighting functions, W_1 (pre-compensator) and W_2 (post-compensator), for shaping the original plant G_0 so that the desired open loop shape is achieved. In this approach, the shaped plant is formulated as normalized co-prime factor, which separates the shaped plant G_s into normalized nominator N_s and denominator M_s factors [8]. Note that, $G_s = W_2 G_0 W_1 = N_s M_s^{-1}$.

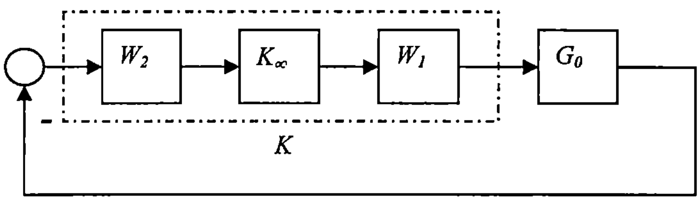


Figure 1. H_∞ loop shaping design [8].

The following steps can be applied to design the H_∞ loop shaping controller.

Step 1 Shape the singular values of the nominal plant G_o by using a pre-compensator W_1 and/or a post-compensator W_2 to get the desired loop shape. Normally, the weighting functions W_1 and W_2 can be chosen as

$$W_1 = K_W \frac{s+a}{s+b} \text{ and } W_2 = I \qquad (1)$$

where K_W, a and b are positive values. b is typically chosen as a small number (<<1) for an integral action. W_2 can be chosen as a constant since the effect of the sensor noise is negligible when the use of good sensor is assumed [9]. If the shaped plant $G_s = N_s M_s^{-1}$, the perturbed plant is written as

$$G_\Delta = (N_s + \Delta_{N_s})(M_s + \Delta_{M_s})^{-1} \qquad (2)$$

where Δ_{Ns} and Δ_{Ms} are stable, unknown representing the uncertainty satisfying $\left\| \Delta_{Ns}, \Delta_{Ms} \right\|_\infty \le \varepsilon$, ε is the uncertainty boundary called stability margin. There are some guidelines for selecting the weight available in [9].

Step 2 Calculate ε_{opt}, where [8]

$$\varepsilon_{opt} = \left(\inf_{K\,stabilizing} \left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (I + G_s K_\infty)^{-1} M_s^{-1} \right\|_\infty \right)^{-1} \qquad (3)$$

To determine ε_{opt}, there is a unique method explained in appendix A. ε_{opt} << 1 indicates that W_1 or W_2 designed in step 1 are incompatible with robust stability requirement. To ensure the robust stability of the nominal plant, the weighting function is selected so that $\varepsilon_{opt} \ge 0.25$ [9]. If ε_{opt} is not satisfied, then go to step 1, adjust the weighting function.

Step 3 Select $\varepsilon < \varepsilon_{opt}$ and then synthesize a controller K_∞ that satisfies [8]

$$\left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (I + G_s K_\infty)^{-1} M_s^{-1} \right\|_\infty \le \varepsilon^{-1} \qquad (4)$$

Controller K_∞ is obtained by solving the sub-optimal control problem in (4). The details of this solving are available in [8]. To determine M_s, there is a method explained in appendix B.

Step 4 Final controller (K) is determined as follow

$$K = W_1 K_\infty W_2 \qquad (5)$$

Fig. 1 shows the controller in H_∞ loop shaping.

.2 PSO based Fixed-Structure H_∞ Loop Shaping Optimization

n the proposed technique, PSO is adopted to the ontroller synthesis. PSO was first proposed by Eberhart nd Kennedy [10] and it has been successfully applied in nany optimization problems. This algorithm is simple, ast and can be programmed in a few steps. The details of 'SO are available in [10]. In the proposed technique, lthough the proposed controller is structured, it still etains the entire robustness and performance guarantee as ong as a satisfactory uncertainty boundary ε is achieved. 'he proposed algorithm is explained as follows.

ssume that the predefined structure controller $K(p)$ has atisfied parameters p. Based on the concept of H_∞ loop haping, optimization goal is to find parameters p in ontroller $K(p)$ that minimize infinity norm from isturbances w to states z, $\|T_{zw}\|_\infty$. Let define the final ontroller K as

$$K = K(p)W_2 \qquad (6)$$

ssuming that W_1 are invertible, From (5) then it is btained that

$$K_\infty = W_1^{-1}K(p) \qquad (7)$$

n many cases, the weight W_2 is selected as I. However, if V_2 is a transfer function matrix, then the final controller 1 (5) is the transfer function from the series connection of ixed-structure controller and filter W_2. Substituting (7) nto (4), the ∞-norm of the transfer function matrix from isturbances to states, $\|T_{zw}\|_\infty$, which is subjected to be ninimized can be written as

$$J_{cost} = \gamma = \|T_{zw}\|_\infty = \left\| \begin{bmatrix} I \\ W_1^{-1}K(p) \end{bmatrix} (I + G_s W_1^{-1}K(p))^{-1} M_s^{-1} \right\|_\infty \qquad (8)$$

'he optimization problem can be written as

$$\text{Maximize} \quad \left\| \begin{bmatrix} I \\ W_1^{-1}K(p) \end{bmatrix} (I + G_s W_1^{-1}K(p))^{-1} M_s^{-1} \right\|_\infty^{-1}$$

$$\text{Subject to} \quad p_{i,\min} < p_i < p_{i,\max},$$

vhere $p_{i,\min}$ and $p_{i,\max}$ are the lower and upper bounds f the parameter p_i in controller $K(p)$, respectively. The itness function in the controller synthesis can be written s

$$\text{Fitness (J)} = \begin{cases} \left(\left\| \begin{bmatrix} I \\ W_1^{-1}K(p) \end{bmatrix} (I + G_s W_1^{-1}K(p))^{-1} M_s^{-1} \right\|_\infty \right)^{-1} & \text{if } K \text{ stabilizes the plant} \\ 0.0001 & \text{otherwise} \end{cases} \qquad (9)$$

The fitness is set to a small value (in this case is .0001) if K does not stabilize the plant. The proposed lgorithm is summarized as follows.

Weight Selection

tep 1 Select the weights W_1 and W_2 to achieve the erformance and desired loop shape.

Step 2 Evaluate ε_{opt} using (3). If $\varepsilon_{opt} < 0.25$, then back to step 1 to change the weights.

-Controller synthesis

Step 3 Select a controller structure $K(p)$ and initialize several sets of parameters p as swarm in the 1st iteration. Define the PSO parameters and control parameter ranges. In this case, each p is a particle.

Step 4 Use the PSO to find the optimal control parameter, p^*.

Step 5 Check performances in both frequency and time domains. If the performance is not satisfied such as too low ε (too low fitness function), then go to step 3 to change the structure of controller. Low ε indicates that the selected control structure is not suitable for the problem.

PSO algorithm used in this paper is briefly described as following steps:

Specify the parameters in PSO such as population size (n), upper and lower bounds of problem space, fitness function (J), maximum and minimum velocity of particles (V_{max}, V_{min}), and etc.

1. Initialize n particles with random positions within upper and lower bounds of the problem space. Set iteration count as $iter = 1$.
2. Evaluate the fitness function (J) of each particle using (9).
3. For each particle, find the best position found by particle i call it X_{pi} and let the fitness value associated with it be J_{pbesti}. At first iteration, position of each particle and its fitness value of i^{th} particle is set to X_{pi} and J_{pbesti}, respectively.
4. Find a best position found by swarm call it G which is the position that maximum fitness value is obtained. Let the fitness value associated with it be J_{Gbest}. To find G the following pseudo code is adopted:

```
(At first iteration set J_gbest, =0)
    For i = 1 to n do
        If J_pbesti > J_gbest, then
            G = X_pi, J_Gbest = J_pbesti
    end;
```

5. Update the inertia weight by following equation

$$Q = Q_{\max} - \frac{Q_{\max} - Q_{\min}}{iter_{\max}} iter$$

where Q is inertia weight, $Q_{\max}$ and $Q_{\min}$ are the specified values of maximum and minimum inertia weights, respectively, $iter$ and $iter_{\max}$ are the iteration count and maximum iteration, respectively.

6. Update the velocity and position of each particle. For the particle i, the updated velocity and position can be determined by following equations.

$$v_i(iter+1) = Qv_i(iter) + \alpha_1[\gamma_{1i}(X_{pi} - X_i(iter)] + \alpha_2[\gamma_{2i}(G - X_i(iter)]$$
$$X_i(iter+1) = X_i(iter) + v_i(iter+1)$$

where v is the velocity of particle, α_1 and α_2 are the specified acceleration coefficients, X_p is the best position ound by i^{th} particle, G is the best position found by warm (global best), γ_{1i} and γ_{1i} are the random numbers n the range [0,1]. Note that the velocity must be within he specified range ($[V_{min}\ ,\ V_{max}]$). If not, set it to the imiting values.

7. Increment iteration for a step. (*iter* = *iter*+1)
8. Stop if convergence criteria are met, otherwise go o step 2.

. Simulation Results

n this paper, the control system of 24-tray tower eparating methanol and water is studied. The dynamic nodel in this study is taken from process control literature 11] which is the transfer function model for controlling he temperature on the 4th and 17th trays; that is,

$$G_0=\begin{bmatrix} y_1 \\ y_2 \end{bmatrix}=\begin{bmatrix} t_{17} \\ t_4 \end{bmatrix}=\begin{bmatrix} \dfrac{-2.2e^{-s}}{7s+1} & \dfrac{1.3e^{-0.3s}}{7s+1} \\ \dfrac{-2.8e^{-1.8s}}{9.5s+1} & \dfrac{4.3e^{-0.35s}}{9.2s+1} \end{bmatrix}\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (10)$$

vhere t_{17} and t_4 are the temperature on the 4th and 17th rays, respectively, u_1 and u_2 are the input of the 4th and 7th trays, respectively. y_1 and y_2 are the outputs of the 4th nd 17th trays, respectively. As shown in (10), this is a table plant with moderate time delays and interaction etween its channels. In the design, the delay terms in the nodel are approximated by the 2nd order pade pproximation method.

o design a robust H∞ loop shaping control, the diagonal veights W_1 and W_2 are selected as follows [5]:

$$W_1=\begin{bmatrix} \dfrac{5s+2}{s+0.001} & 0 \\ 0 & \dfrac{5s+2}{s+0.001} \end{bmatrix},\quad W_2=\begin{bmatrix} \dfrac{10}{s+10} & 0 \\ 0 & \dfrac{10}{s+10} \end{bmatrix} \quad (11)$$

Vith these weighting functions, the crossover frequency f the desired system is 2 rad/s. Singular value plots of pen loop transfer function for the nominal plant and haped plant are shown in Fig. 2 (a). As shown in this igure, at low frequency, the gain of shaped plant is much arger than that of the nominal plant. This makes the lesigned system good in terms of performance tracking nd disturbance rejection. Based on (3), the optimal tability margin (ε_{opt}) is founded to be 0.361. This means hat the selected weights are compatible with robust tability requirement in the problem. By the conventional H∞ loop shaping procedure, ε is set to be 0.328, which is ess than the optimal value. Based on the procedure lescribed in section 2.1, H∞ loop shaping controller can e designed as following.

$$K(HLS)=W_1K_\infty W_2=W_1\begin{bmatrix} K11_\infty & K12_\infty \\ K21_\infty & K22_\infty \end{bmatrix}W_2 \quad (12)$$

The controller in each element of controller matrix K_∞ is 20th order controller and complicated. It is not easy to implement practically.

Next, fixed-structure robust controllers are designed. The structure of controller is selected as PID with first-order derivative filter. These structures are expressed in (13) and (14) for centralized and decentralized controllers, respectively. K_p, K_i, K_d, and τ_d are parameters to be evaluated.

$$K(p)=\begin{bmatrix} K_{p1}+\dfrac{K_{i1}}{s}+\dfrac{K_{d1}s}{\tau_d s+1} & K_{p2}+\dfrac{K_{i2}}{s}+\dfrac{K_{d2}s}{\tau_d s+1} \\ K_{p3}+\dfrac{K_{i3}}{s}+\dfrac{K_{d3}s}{\tau_d s+1} & K_{p4}+\dfrac{K_{i4}}{s}+\dfrac{K_{d4}s}{\tau_d s+1} \end{bmatrix} \quad (13)$$

$$K_p=\begin{bmatrix} K_{p1} & K_{p2} \\ K_{p3} & K_{p4} \end{bmatrix}, K_i=\begin{bmatrix} K_{i1} & K_{i2} \\ K_{i3} & K_{i4} \end{bmatrix}, K_d=\begin{bmatrix} K_{d1} & K_{d2} \\ K_{d3} & K_{d4} \end{bmatrix}$$

$$K(p)=\begin{bmatrix} K_{p1}+\dfrac{K_{i1}}{s}+\dfrac{K_{d1}s}{\tau_d s+1} & 0 \\ 0 & K_{p4}+\dfrac{K_{i4}}{s}+\dfrac{K_{d4}s}{\tau_d s+1} \end{bmatrix} \quad (14)$$

$$K_p=\begin{bmatrix} K_{p1} & 0 \\ 0 & K_{p4} \end{bmatrix}, K_i=\begin{bmatrix} K_{i1} & 0 \\ 0 & K_{i4} \end{bmatrix}, K_d=\begin{bmatrix} K_{d1} & 0 \\ 0 & K_{d4} \end{bmatrix}$$

In the optimization problem, the upper and lower bounds of controller parameters and PSO parameters are set as follows: $K_p \in$ [-10, 10], $K_i \in$ [-10, 10], $K_d \in$ [-5, 5], $\tau_d \in$ [0.01, 1], population size = 500, minimum and maximum velocities are 0 and 2 respectively, acceleration coefficients = 2.1, minimum and maximum inertia weights are 0.6 and 0.9, respectively, maximum iteration = 80. As shown in the above controller parameters range, the selection of upper and lower bounds is easily carried out by observing the performance weight W_1. After running the PSO, the optimal controllers are found to be

Centralized controller case:

$$K_p=\begin{bmatrix} 2.6003 & -0.75154 \\ -1.1158 & -2.4684 \end{bmatrix}, K_i=\begin{bmatrix} 0.87399 & -0.28553 \\ 0.096274 & -0.96078 \end{bmatrix},$$

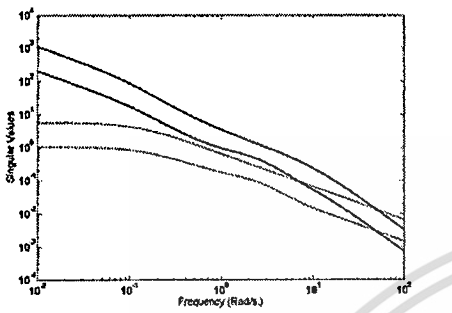
$$K_d=\begin{bmatrix} 0.76181 & -0.30821 \\ -1.4953 & -0.028287 \end{bmatrix}, \tau_d=0.14945 \quad (15)$$

Decentralized controller case:

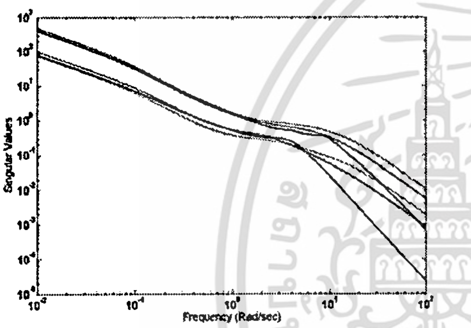
$$K_p=\begin{bmatrix} 1.9277 & 0 \\ 0 & -2.4511 \end{bmatrix}, K_i=\begin{bmatrix} 0.71976 & 0 \\ 0 & -0.74521 \end{bmatrix},$$

$$K_d=\begin{bmatrix} 0.80265 & 0 \\ 0 & -1.1439 \end{bmatrix}, \tau_d=0.07566 \quad (16)$$

Note that the controllers in (12), (15), and (16) are the controllers in positive feedback control system. The stability margins obtained from the proposed centralized and decentralized controllers are 0.343 and 0.27371, respectively. The singular values are plotted to verify the proposed algorithm. Fig. 2 (b) shows comparison of the loop shapes by the proposed controllers and HLS. As seen n this figure, loop shapes by the proposed controllers and *HLS* are close to the desired loop shape. It is verified that he proposed technique and conventional HLS are efficiently adopted to design a robust controller. Fig.3 shows plots of convergence of objective function (stability margin) versus iterations by PSO. As shown in he figure, the optimal robust PID controllers provide satisfied stability margins at 0.34269 and 0.27371 for centralized and decentralized controllers, respectively.



(a)



(b)

Figure 2. Singular value plots of open loop transfer function of (a) the nominal plant (dash line) and shaped plant (solid line) (b) the loop shape by the proposed controllers (Red line: Centralized PID, dash line: Decentralized PID) and HLS (Blue line).

By the results, it is clearly shown that the stability margin of the system from decentralized controller (ε =0.27371) is less than that of HLS and centralized controllers. However, if such stability margin is satisfied for the control system (more than the specified stability margin), decentralized controller can be applied to control the plant and the advantages of using decentralized control scheme such as simple controller, less complexity, and etc. will be achieved. To evaluate the performance of the proposed system, step responses of the close loop system from conventional H_∞ loop shaping (HLS), proposed centralized and decentralized controllers are investigated. As seen in Fig. 4, the responses from the proposed controllers are almost the same as those of HLS. Table 1 shows the results from the proposed technique in comparison with the results from previous research works [5,6]. As shown in this table, the optimal solution in [5, 6] are depended on the selection of initial solution which is not desirable for the controller design. Although trial and error for choosing this initial solution can be employed; however, there is no systematic method to select such value. As shown in Table 1, the stability margin using method in [6] is reduced when the other reasonable initial solution was used. In the proposed technique, the design is more flexible than the previous works by selecting the appropriate upper and lower bounds of solution instead of selection of the initial solution. Moreover, because PSO technique is based on the concept of global optimization searching, the problem of local minima is reduced. As shown in Table 1, the stability margin of the optimal controller designed by the proposed technique is much better than that of the conventional technique in [5]. In the decentralized controller design, the stability margin of the proposed controller is still better than that of the centralized controller from [5].

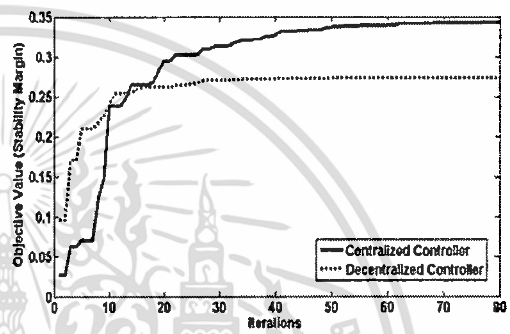


Figure 3. Convergence of the fitness value.

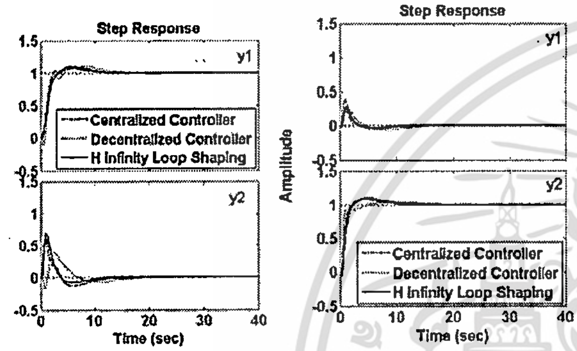
Table 1

Comparisons of the results to the previous works. (Note that: *Technique in [6] (I)* means the results when the best initial solution is selected, *Technique in [6] (II)* means the results when the other reasonable initial solution is selected, N/A means not available.)

	Optimal Stability Margin			
	Proposed technique	Technique in [5]	Technique in [6] (I)	Technique in [6] (II)
Centralized PID Controller	0.343	0.249	0.343	0.328
Decentralized PID Controller	0.274	N/A	N/A	N/A

4. Conclusion

In this paper, a PSO based fixed-structure H_∞ loop shaping controller designed for MIMO system is proposed. Based on the concept of the convention H_∞ loop shaping, only a single index, stability margin, ε, is used to indicate performance and robustness of the designed controller. In conventional H_∞ loop shaping, the designed controller is complicated and difficult to apply this controller in practical works. For the proposed PID control, the optimal solutions of ε after running PSO for 80 generations are 0.343 and 0.27371 for centralized and decentralized controllers, respectively. These values indicate that the designed controllers are compatible with the specified open loop shape and also guarantee robustness. In the simulation results, the step responses of the proposed controllers are almost identical to those of the controller designed by H_∞ loop shaping method. However, because of the complicated controller in the conventional design, the proposed approach offers a significant improvement in practical control viewpoint by simplifying the controller structure, reducing the controller order and still retaining the robust performance. Decentralized controller can be used if its stability margin is accepted. By comparison with the previous works in [5,6], the optimal stability margin obtained by the proposed technique is much better than that of the method in [5] and there is no the problem of initial solution selection which is the problem of the methods in [5, 6].



(a) (b)

Figure 4. Responses from the proposed PID controllers and HLS when the step command is applied to control the output (a) y_1 and (b) y_2.

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Appendix A

Given a shaped plant G_s and A, B, C, D represent the shaped plant in the state-space form. To determine ε_{opt}, there is a unique method as follows [8].

$$\gamma_{opt} = \varepsilon_{opt}^{-1} = (1 + \lambda_{\max}(XZ))^{1/2}$$

where X and Z are the solutions of two Riccati in (A.1) and (A.2) respectively, λ_{max} is the maximum eigenvalue.

$$(A - BS^{-1}D^TC)Z + Z(A - BS^{-1}D^TC)^T - ZC^TR^{-1}CZ + BS^{-1}B^T = 0 \quad \text{(A.1)}$$

$$(A - BS^{-1}D^TC)^TX + X(A - BS^{-1}D^TC) - XBS^{-1}B^TX + C^TR^{-1}C = 0 \quad \text{(A.2)}$$

where $S = I + D^TD$, $R = I + DD^T$.

Appendix B

Given a shaped plant G_s and A, B, C, D represent the shaped plant in the state-space form. If G_s has a minimal state-space realization

$$G_s = \left[\begin{array}{c|c} A & B \\ \hline C & D \end{array}\right] \quad \text{(B.1)}$$

Then a minimal state-space realization of a normalized left coprime factorization is given by [8].

$$[N, M] = \left[\begin{array}{c|cc} A + HC & B + HD & H \\ \hline R^{-1/2}C & R^{-1/2}D & R^{-1/2} \end{array}\right] \quad \text{(B.2)}$$

where $H = -(BD^T + ZC^T)R^{-1}$, $R = I + DD^T$.

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Structured Robust Loop shaping control for HIMAT System Using PSO

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Abstract. Robust loop shaping control is a feasible method for designing a robust controller; however, the controller designed by this method is complicated and difficult to implement practically. To overcome this problem, in this paper, a new design technique of a fixed-structure robust loop shaping controller for a highly maneuverable airplane, HIMAT, is proposed. The performance and robust stability conditions of the designed system satisfying H_∞ loop shaping control are formulated as the objective function in the optimization problem. Particle Swarm Optimization (PSO) technique is adopted to solve this problem and to achieve the control parameters of the proposed controller. Simulation results demonstrate that the proposed approach is numerically efficient and leads to performance comparable to that of the other method.

Keywords: H_∞ loop shaping control, robust control, particle swarm optimization, HIMAT system, fixed-structure controller.

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INTRODUCTION

In the past decades, many immense developments in robust control techniques have been proposed and the results of those are utilized in many control systems. As shown in previous works, H_∞ optimal control is a powerful technique to design a robust controller for system under conditions of uncertainty, parameter change, and disturbance. However, the order of controller designed by this technique is much higher than that of the plant. It is not easy to implement this controller in practical applications. In industrial applications, structures such as PID, lead-lag compensators are widely used because their structures are simple, tuning parameters are fewer, and they are lower order. Unfortunately, tuning of control parameters of such controllers for achieving a good performance and robustness is difficult. To solve this problem, the design of fixed-structure robust controller has been proposed. Fixed-structure robust controller has become an interesting area of research because of its simple structure and acceptable controller order. However, the design of this controller by using analytical methods remains difficult. To simplify the problem, searching algorithms such as genetic algorithm, particle swarm optimization technique, tabu-

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search, etc., can be employed. Several approaches to design a fixed-structure robust controller were proposed in [1-3, 5-7]. In [1], a robust H_∞ optimal control problem with structure specified controller was solved by using genetic algorithm (GA). As concluded in [1], genetic algorithm is a simple and efficient tool to design a fixed-structure H_∞ optimal controller. Bor-Sen.Chen. *et. al.*[2], proposed a PID design algorithm for mixed H_2/H_∞ control. In their paper, PID control parameters were tuned in the stability domain to achieve mixed H_2/H_∞ optimal control. A similar work was proposed in [3] by using the intelligent genetic algorithm to solve the mixed H_2/H_∞ optimal control problem. The techniques in [1-3] are based on the concept of H_∞ optimal control which two appropriate weights for both the uncertainty of the model and the performance are essentially chosen. A difficulty with the H_∞ optimal control approach is that the appropriate selection of close-loop objectives and weights is not straightforward [4]. Moreover, especially in MIMO system, it is not easy to specify the uncertainty weight in practice. Alternatively, MIMO controller can be designed by using H_∞ loop shaping control [4] which is a simple and efficient technique for designing a robust controller. Uncertainties in this approach are modeled as normalized co-prime factors; this uncertainty model does not represent actual physical uncertainty, which usually is unknown in real problems. This technique requires only two specified weights, pre- and post-compensator weights, for shaping the nominal plant so that the desired open loop shape is achieved. Fortunately, the selection of such weights is based on the concept of classical loop shaping which is a well known technique in the controller design. By the reasons mentioned above, this technique is simpler and more intuitive than other robust control techniques. However, the controller designed by H_∞ loop shaping is still complicated. To overcome this problem, several approaches have been proposed to design a fixed-structure H_∞ loop shaping controller, such as a state-space approach by A. Umut. Genc in 2000 [5], genetic algorithms based fixed-structure H_∞ loop shaping by Somyot and Manukid in 2004 [6], etc. The method in [5] is based on the concept of state space approach and BMI optimization. Unfortunately, the chance of reaching a satisfactory solution of this approach depends on the initial controller chosen and the problem of the local minima is often occurred. In [6], a global optimization method was adopted to design the fixed-structure robust H_∞ loop shaping controller; however, the designed controllers in [6] were only implemented on a pneumatic servo system which is a SISO system. In [7], the same technique as [6] was adopted to design a robust controller of a boost converter; however, this application is also a SISO system. In this paper, PSO is proposed to synthesize a fixed-structure H_∞ loop shaping controller for HIMAT system. Based on the concept of PSO technique, the choosing of initial controller required in the method in [5] is not necessary and the problem of local minima is reduced. Structure of controller in the proposed technique is selectable; in this paper, two fixed-structure controllers, centralized and decentralized PID controllers, are designed. Simulation results show that the controller designed by the proposed approach has a good performance and robustness as well as simple structure. This allows our designed controller to be implemented practically and reduces the gap between the theoretical and practical approach.

The remainder of this paper is organized as follows. Conventional H_∞ loop shaping and the proposed technique are discussed in section 2. PSO algorithm is also described in this section. Section 3 demonstrates a design example and results. And, finally, in section 4 the paper is summarized with some final remarks.

H_∞ LOOP SHAPING CONTROL AND PROPOSED TECHNIQUE

This section illustrates the concepts of conventional H_∞ loop shaping control and the proposed technique.

Conventional H_∞ Loop Shaping Control

H_∞ loop shaping control is an efficient method to design a robust controller. This approach requires two weighting functions, W_1 (pre-compensator) and W_2 (post-compensator), for shaping the original plant G_0 so that the desired open loop shape is achieved. In this approach, the shaped plant is formulated as normalized co-prime factor, which separates the shaped plant G_s into normalized nominator N_s and denominator M_s factors [8].

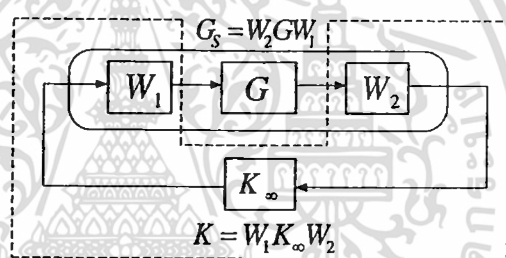


FIGURE 1. H_∞ loop shaping design.

The following steps can be applied to design H_∞ loop shaping controller [4].

Step 1 Shape the singular values of the nominal plant G_o by using a pre-compensator W_1 and/or a post-compensator W_2 to get the desired loop shape. W_2 can be chosen as a constant since the effect of the sensor noise is negligible when the use of good sensor is assumed [9].

$$G_s = W_2 G_0 W_1 = N_s M_s^{-1} \tag{1}$$

Based on the concept of H_∞ loop shaping, the perturbed plant is written as

$$G_\Delta = (N_s + \Delta_{Ns})(M_s + \Delta_{Ms})^{-1} \tag{2}$$

where Δ_{Ns} and Δ_{Ms} are stable, unknown representing the uncertainty satisfying $\|\Delta_{Ns}, \Delta_{Ms}\|_\infty \le \varepsilon$, ε is the uncertainty boundary called stability margin. There are some guidelines for selecting the weight available in [9].

Step 2 Calculate ε_{opt}, where

$$\varepsilon_{opt} = \left(\inf_{K\,stabilizing} \left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (I - G_s K_\infty)^{-1} [I \quad G_s] \right\|_\infty \right)^{-1} \quad (3)$$

To determine ε_{opt}, there is a unique method explained in appendix A. $\varepsilon_{opt} << 1$ indicates that W_1 or W_2 designed in step 1 are incompatible with robust stability requirement. To ensure the robust stability of the nominal plant, the weighting functions are selected so that $\varepsilon_{opt} \geq 0.25$ [9]. If ε_{opt} is not satisfied, then go to step 1, adjust the weighting functions.

Step 3 Select $\varepsilon < \varepsilon_{opt}$ and then synthesize a controller K_∞ that satisfies [4]

$$\|T_{ZW}\|_\infty = \left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (I - G_s K_\infty)^{-1} [I \quad G_s] \right\|_\infty \leq \varepsilon^{-1} \quad (4)$$

where $\|T_{zw}\|_\infty$ is the infinity norm from the disturbances w to state z. Controller K_∞ is obtained by solving the sub-optimal control problem in (4). The details of this solving are available in [8].

Step 4 Final controller (K) is determined as follow

$$K = W_1 K_\infty W_2 \quad (5)$$

Fig. 1 shows the controller in H_∞ loop shaping control.

PSO based Fixed-Structure H_∞ Loop Shaping Optimization

In the proposed technique, PSO is adopted to design a fixed-structure robust controller. A similar work was presented in [5]. However, the problem in [5] was formulated by using a BMI-based optimization approach unlike the PSO approach taken in this paper. In [5], initial solution required in the design procedure strongly influences the performance of final solution. Moreover, there is no systematic method to select such initial value. In the proposed technique, the design is more flexible than the previous work [5] by selecting the appropriate upper and lower bounds of solution. In the design, boundary of solution of PSO is selected by considering the pre-compensator weight. Normally, this weight is specified by first or second order transfer functions at the diagonals entries of W_1. Fortunately, it is not difficult to transform these transfer functions to PI/PID structure. Since the fixed-structure controller in the paper is PID, thus, the choosing of boundary of solution by considering weight, W_1, can be done easily. In addition, because PSO technique is based on the concept of global optimization searching, the problem of local minima is reduced.

PSO was first proposed by Eberhart and Kennedy [10]. This technique is a population-based optimization problem-solving algorithm. Fig.2 shows the swarm's movement which is the basic idea of PSO. As seen in this figure, a bird represents the particle and the position of each particle represents the candidate solution. Population is formed by a number of particles. In the PSO, particles fly around the problem space until the stopping criteria are met. This algorithm is simple, fast and can be programmed easily. During the flight, the velocity and position of each particle are updated according to its own and its companion's fitness value. To illustrate the strategies of PSO, the following equation is shown.

$$v_i(iter+1) = Qv_i(iter) + \alpha_1[\gamma_{1i}(X_{pi} - X_i(iter)] + \alpha_2[\gamma_{2i}(G - X_i(iter)] \qquad (6)$$

where Q is the momentum coefficient, v_i is the velocity of i^{th} particle, *iter* is the iteration count, α_1 and α_2 are the specified acceleration coefficients, X_{pi} is the best position found by i^{th} particle, G is the best position found by swarm (global best), γ_{1i} and γ_{2i} are the random numbers in the range [0,1]. Note that the velocity must be within the specified range [V_{min} , V_{max}]. If not, set it to the limiting values. As shown in (6), there are three terms in the equation. By these terms, the advantages of local minimum searching, global minimum searching, local optima avoidance and the information sharing among particles are achieved and the particle can reach the best solution. The details of PSO are available in [10].

FIGURE 2. The movement of a swarm.

In the proposed technique, although the controller is structured, it still retains the entire robustness and performance guarantee as long as a satisfactory uncertainty boundary ε is achieved. The proposed algorithm is explained as follows. Assume that the predefined structure controller $K(p)$ has satisfied parameters p. Based on the concept of H_∞ loop shaping, optimization goal is to find parameters p in controller $K(p)$ that minimize infinity norm from disturbances w to states z, $\|T_{zw}\|_\infty$. In the proposed technique, the final controller K is defined as

$$K = K(p)W_2 \qquad (7)$$

Assuming that W_1 are invertible, from (5) then it is obtained that

$$K_\infty = W_1^{-1}K(p) \qquad (8)$$

In many cases, the weight W_2 is selected as identity matrix I. However, if W_2 is a transfer function matrix, then the final controller is the controller $K(p)$ in series with the weight W_2. By substituting (8) into (4), the ∞-norm of the transfer function matrix from disturbances to states, $\|T_{zw}\|_\infty$, which is subjected to be minimized can be written as

$$J_{cost} = \gamma = \|T_{zw}\|_\infty = \left\| \begin{bmatrix} I \\ W_1^{-1}K(p) \end{bmatrix} (I - W_2 G_0 K(p))^{-1} [I \quad G_s] \right\|_\infty$$

The optimization problem can be written as

Maximize $\left\| \begin{bmatrix} I \\ W_1^{-1}K(p) \end{bmatrix} (I - W_2 G_0 K(p))^{-1} [I \quad G_s] \right\|_\infty^{-1}$

Subject to $p_{i,\min} < p_i < p_{i,\max}$,

where $p_{i,\min}$ and $p_{i,\max}$ are the lower and upper bound values of the parameter p_i in the parameter vector p, respectively. Thus, the fitness function in the controller synthesis can be written as

$$\text{Fitness (J)} = \begin{cases} \left(\left\| \begin{bmatrix} I \\ W_1^{-1}K(p) \end{bmatrix} (I - W_2 G_0 K(p))^{-1} [I \quad G_s] \right\|_\infty \right)^{-1} & \text{if } K \text{ stabilizes the plant} \\ 0.0001 & \text{otherwise} \end{cases} \tag{9}$$

The fitness is set to a small value (in this case is 0.0001) if K does not stabilize the plant. Our proposed algorithm is summarized as follows.

-Weight Selection

Step 1 Select the weights W_1 and W_2 to achieve the performance and desired loop shape.

Step 2 Evaluate ε_{opt} using (3). If $\varepsilon_{opt} < 0.25$, then back to step 1 to change the weights.

-Controller synthesis

Step 3 Select a controller structure $K(p)$ and define the PSO parameters and control parameter ranges. Initialize several sets of parameters p as swarm in the 1^{st} iteration. In this case, each p is a particle.

Step 4 Use the PSO to find the optimal control parameter, p^*.

Step 5 Check performances in both frequency and time domains. If the performance is not satisfied such as too low ε (too low fitness function), then go to step 3 to change the structure of controller. Low ε indicates that the selected control structure is not suitable for the problem.

Standard PSO algorithm used in step 4 of the proposed technique is briefly described as follows.

Specify the parameters in PSO such as population size (n), upper and lower bound values of problem space, fitness function (J), maximum and minimum velocity of particles (V_{max} and V_{min}, respectively), maximum and minimum inertia weights ($Q_{\max}$ and $Q_{\min}$, respectively).

1. Initialize n particles with random positions within upper and lower bound values of the problem space. Set iteration count as $iter = 1$.
2. Evaluate the fitness function (J) of each particle using (9).
3. For each particle, find the best position found by particle i call it X_{pi} and let the fitness value associated with it be J_{pbesti}. At first iteration, position of each particle and its fitness value of i^{th} particle are set to X_{pi} and J_{pbesti}, respectively.
4. Find a best position found by swarm call it G which is the position that maximum fitness value is obtained. Let the fitness value associated with it be J_{Gbest}. To find G the following algorithm described by pseudo code is adopted.

   (At first iteration set J_{gbest}, =0)
   For i = 1 to n do
       If $J_{pbesti} > J_{gbest}$, then
           $G = X_{pi}$, $J_{Gbest} = J_{pbesti}$
       end;
5. Update the inertia weight by following equation

$$Q = Q_{\max} - \frac{Q_{\max} - Q_{\min}}{iter_{\max}} iter$$

   where Q is inertia weight, $iter$ and $iter_{\max}$ are the iteration count and maximum iteration, respectively.
6. Update the velocity and position of each particle. For the particle i, the updated velocity and position can be determined by following equations.

$$v_i(iter+1) = Qv_i(iter) + \alpha_1[\gamma_{1i}(X_{pi} - X_i(iter))] + \alpha_2[\gamma_{2i}(G - X_i(iter))]$$

$$X_i(iter+1) = X_i(iter) + v_i(iter+1)$$

7. Increment iteration for a step. ($iter = iter+1$)
8. Stop if the convergence or stopping criteria are met, otherwise go to step 2.

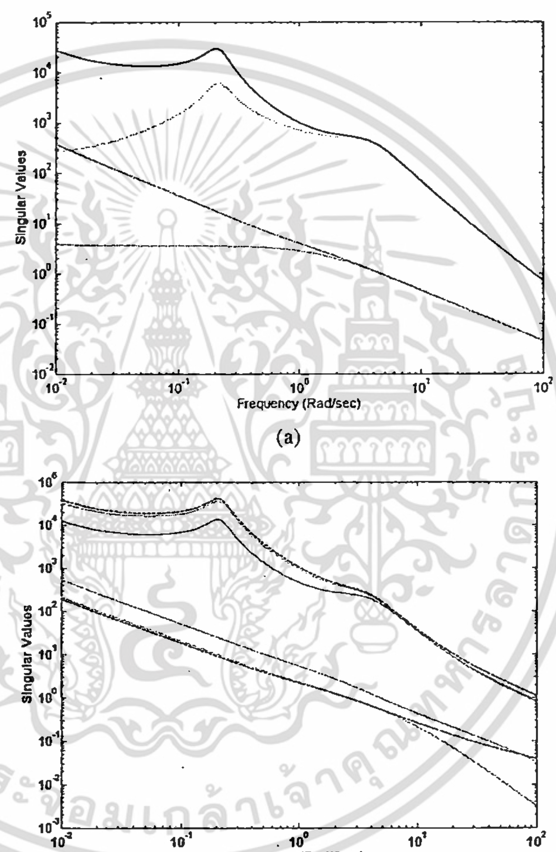
SIMULATION RESULTS

In this paper, the design of pitch axis controller for an experimental highly maneuverable airplane, HIMAT, is studied. The dynamic model of this plant is taken from the μ-synthesis and analysis toolbox user's guide [11]. The state vector of this plant consists of the four variables which are forward velocity, angle-of-attack, pitch rate, and pitch angle. The control inputs are the elevon and the canard. The measured variables are angle-of-attack and pitch angle. The details of this plant are given in appendix B. The design objective is to reject disturbances up to about 1 rad/s in the presence of substantial plant uncertainty above 100 rad/s [5]. In this problem, the pre- and post-compensator weights are chosen as [5].

$$W_1 = \begin{bmatrix} \frac{s+1}{s+0.001} & 0 \\ 0 & \frac{s+1}{s+0.001} \end{bmatrix}, \quad W_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{10}$$

Singular values of HIMAT and desired loop shape are plotted in Fig. 3 (a). As seen in this figure, the bandwidth and performance are significantly improved by the compensator weights. The shaped plant has large gains at low frequencies for performance and small gains at high frequencies for noise attenuation. With these weighting functions, the robust requirement is satisfied.

By using (3), the optimal stability margin of the shaped plant is found to be 0.436. This value indicates that the selected weights are compatible with robust stability requirement in the problem. To design the HLS controller, stability margin 0.3964 is selected. As a result, the final controller (full order HLS controller) is 7^{th} order and complicated.



(b)

FIGURE 3. Open loop shape of (a) the nominal plant (Red line) and shaped plant (Black line) (b) the loop shape by the proposed controllers (Red line: Centralized PID, dash line: Decentralized PID) and HLS (Blue line).

Next, two fixed-structure robust controllers are designed. The structure of controllers is selected as PID with first-order derivative filter. Accordingly, these controllers are simple and easy to implement in real applications. These controllers are expressed in

(11) and (12) for centralized and decentralized controllers, respectively. K_p, K_i, K_d, and τ_d are parameters to be evaluated.

Centralized controller:

$$K(p)=\begin{bmatrix} K_{p1}+\frac{K_{i1}}{s}+\frac{K_{d1}s}{\tau_d s+1} & K_{p2}+\frac{K_{i2}}{s}+\frac{K_{d2}s}{\tau_d s+1} \\ K_{p3}+\frac{K_{i3}}{s}+\frac{K_{d3}s}{\tau_d s+1} & K_{p4}+\frac{K_{i4}}{s}+\frac{K_{d4}s}{\tau_d s+1} \end{bmatrix} \quad (11)$$

$$K_p=\begin{bmatrix} K_{p1} & K_{p2} \\ K_{p3} & K_{p4} \end{bmatrix}, K_i=\begin{bmatrix} K_{i1} & K_{i2} \\ K_{i3} & K_{i4} \end{bmatrix}, K_d=\begin{bmatrix} K_{d1} & K_{d2} \\ K_{d3} & K_{d4} \end{bmatrix}$$

Decentralized controller:

$$K(p)=\begin{bmatrix} K_{p1}+\frac{K_{i1}}{s}+\frac{K_{d1}s}{\tau_d s+1} & 0 \\ 0 & K_{p4}+\frac{K_{i4}}{s}+\frac{K_{d4}s}{\tau_d s+1} \end{bmatrix} \quad (12)$$

$$K_p=\begin{bmatrix} K_{p1} & 0 \\ 0 & K_{p4} \end{bmatrix}, K_i=\begin{bmatrix} K_{i1} & 0 \\ 0 & K_{i4} \end{bmatrix}, K_d=\begin{bmatrix} K_{d1} & 0 \\ 0 & K_{d4} \end{bmatrix}$$

In the optimization problem, the upper and lower bounds of control parameters and PSO parameters are set as follows: $K_p \in [-10, 10]$, $K_i \in [-10, 10]$, $K_d \in [-5, 5]$, $\tau_d \in [0.01, 1]$, population size = 300, minimum and maximum velocities are 0 and 2 respectively, acceleration coefficients = 2.1, minimum and maximum inertia weights are 0.6 and 0.9, respectively, maximum iteration = 80. As shown in the above mentioned control parameter ranges, the selection of upper and lower bounds is easily carried out by observing the performance weight W_1. After running the PSO for 80 iterations, the optimal control parameters are found to be

Case I: Centralized controller.

$$K_p=\begin{bmatrix} 0.52601 & 0.14172 \\ 0.47833 & -0.70387 \end{bmatrix}, K_i=\begin{bmatrix} 1.96082 & -0.28352 \\ 2.2261 & -1.224 \end{bmatrix},$$
$$K_d=\begin{bmatrix} 0.007434 & 0.006844 \\ -0.006272 & 0.0016058 \end{bmatrix}, \tau_d=0.0068479 \quad (13)$$

Case II: Decentralized controller.

$$K_p=\begin{bmatrix} 0.5367 & 0 \\ 0 & -0.5659 \end{bmatrix}, K_i=\begin{bmatrix} 1.488 & 0 \\ 0 & -0.4909 \end{bmatrix},$$
$$K_d=\begin{bmatrix} 0.01569 & 0 \\ 0 & -0.00499 \end{bmatrix}, \tau_d=0.0085855 \quad (14)$$

(11) and (12) for centralized and decentralized controllers, respectively. K_p, K_i, K_d, and τ_d are parameters to be evaluated.

Centralized controller:

$$K(p)=\begin{bmatrix} K_{p1}+\frac{K_{i1}}{s}+\frac{K_{d1}s}{\tau_d s+1} & K_{p2}+\frac{K_{i2}}{s}+\frac{K_{d2}s}{\tau_d s+1} \\ K_{p3}+\frac{K_{i3}}{s}+\frac{K_{d3}s}{\tau_d s+1} & K_{p4}+\frac{K_{i4}}{s}+\frac{K_{d4}s}{\tau_d s+1} \end{bmatrix} \tag{11}$$
$$K_p=\begin{bmatrix} K_{p1} & K_{p2} \\ K_{p3} & K_{p4} \end{bmatrix}, K_i=\begin{bmatrix} K_{i1} & K_{i2} \\ K_{i3} & K_{i4} \end{bmatrix}, K_d=\begin{bmatrix} K_{d1} & K_{d2} \\ K_{d3} & K_{d4} \end{bmatrix}$$

Decentralized controller:

$$K(p)=\begin{bmatrix} K_{p1}+\frac{K_{i1}}{s}+\frac{K_{d1}s}{\tau_d s+1} & 0 \\ 0 & K_{p4}+\frac{K_{i4}}{s}+\frac{K_{d4}s}{\tau_d s+1} \end{bmatrix} \tag{12}$$
$$K_p=\begin{bmatrix} K_{p1} & 0 \\ 0 & K_{p4} \end{bmatrix}, K_i=\begin{bmatrix} K_{i1} & 0 \\ 0 & K_{i4} \end{bmatrix}, K_d=\begin{bmatrix} K_{d1} & 0 \\ 0 & K_{d4} \end{bmatrix}$$

In the optimization problem, the upper and lower bounds of control parameters and PSO parameters are set as follows: $K_p \in$ [-10, 10], $K_i \in$ [-10, 10], $K_d \in$ [-5, 5], $\tau_d \in$ [0.01, 1], population size = 300, minimum and maximum velocities are 0 and 2 respectively, acceleration coefficients = 2.1, minimum and maximum inertia weights are 0.6 and 0.9, respectively, maximum iteration = 80. As shown in the above mentioned control parameter ranges, the selection of upper and lower bounds is easily carried out by observing the performance weight W_1. After running the PSO for 80 iterations, the optimal control parameters are found to be

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Case II: Decentralized controller.

$$K_p=\begin{bmatrix} 0.5367 & 0 \\ 0 & -0.5659 \end{bmatrix}, K_i=\begin{bmatrix} 1.488 & 0 \\ 0 & -0.4909 \end{bmatrix}, \\ K_d=\begin{bmatrix} 0.01569 & 0 \\ 0 & -0.00499 \end{bmatrix}, \tau_d=0.0085855 \tag{14}$$

Note that all of the designed controllers in this paper are the controllers in positive feedback control system. Fig. 3 (b) shows comparison of the loop shapes by the proposed controllers and HLS. As seen in this figure, all loop shapes are close to the desired loop shape. Fig. 4 shows plots of convergence of objective function (stability margin) versus iterations by PSO. As seen in this figure, the stability margins obtained from the proposed centralized and decentralized controllers are 0.432 and 0.389 respectively. These values indicate that the robust stability and performance of the designed systems are satisfied.

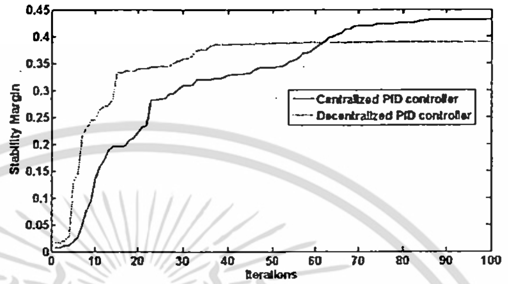

FIGURE 4. Convergence of the fitness value.

In this simulation studies, the robustness and performance of the proposed controllers are compared with those of the controller obtained from [5], that is

$$K_p=\begin{bmatrix}1.3074 & -0.0601\\ 1.3414 & -1.3123\end{bmatrix}, K_i=\begin{bmatrix}1.2729 & -0.0795\\ 1.3609 & -1.2921\end{bmatrix},$$
$$K_d=\begin{bmatrix}0.0077 & 0.0043\\ -0.0069 & -0.0039\end{bmatrix}, \tau_d=\frac{1}{99.5724} \quad (15)$$

The stability margin obtained by the above controller is 0.309. Clearly, the stability margin of the proposed centralized controller is also much better than that of the controller in [5].

Table 1 summarizes the results of stability margin obtained from the proposed controller and others. As the results, the stability margin from the proposed centralized PID controller is better than that of other controllers. Accordingly, the proposed technique is an efficient method to design a fixed-structure robust loop shaping controller. Note that the design of decentralized PID controller was not presented in the previous work [5].

TABLE 1. Comparisons of the stability margins obtained from the controllers.

Controller	Stability Margin
1. Proposed Controller:	
1.1 Centralized PID Controller	0.432
1.2 Decentralized PID Controller	0.389
2. Robust Centralized PID Controller designed by BMI optimization [5]	0.309

CONCLUSIONS

In this paper, a PSO based fixed-structure H_∞ loop shaping controller for HIMAT system is proposed. Based on the concept of conventional H_∞ loop shaping, only a single index, stability margin, ε, is used to indicate performance and robustness of the designed controller. This index is utilized as the objective function of the proposed technique. The resulting stability margins indicate that the proposed controllers are compatible with the specified open loop shape and also guarantee robustness. Moreover, the structure of controller is not restricted to PID. The controller $K(p)$ can be replaced by any fixed-structure controller and the proposed algorithm can still be applied functionally. By comparison with the previous work [5], the optimal stability margin obtained by the proposed technique is also much better than that of the method in [5] and the problem of local minima is reduced by the proposed algorithm. In conclusion, by combining the two approaches of PSO and H_∞ loop shaping; fixed-structure H_∞ loop shaping controller can be designed. Although the design of fixed-structure robust controller is difficult because of its inherently non-convex nonlinear problem, the PSO simplifies the problem by searching the optimal solution. Simulation results demonstrate that the proposed technique is valid and flexible.

APPENDIX A

Given a shaped plant G_s and A, B, C, D represent the shaped plant in the state-space form. To determine ε_{opt}, there is a unique method as follows [8].

$$\gamma_{opt} = \varepsilon_{opt}^{-1} = (1+\lambda_{\max}(XZ))^{1/2}$$

where X and Z are the solutions of two Riccati in (A.1) and (A.2) respectively, λ_{max} is the maximum eigenvalue.

$$(A-BS^{-1}D^TC)Z+Z(A-BS^{-1}D^TC)^T-ZC^TR^{-1}CZ+BS^{-1}B^T=0 \qquad \text{(A.1)}$$

$$(A-BS^{-1}D^TC)^TX+X(A-BS^{-1}D^TC)-XBS^{-1}B^TX+C^TR^{-1}C=0 \qquad \text{(A.2)}$$

where $S = I + D^TD$, $R = I+DD^T$

APPENDIX B

The state vector of HIMAT model consists of vehicle's rigid body variables.

$$x^T = [\delta v, \alpha, q, \theta]$$

where δv is the forward velocity, α is angle between velocity vector and aircraft's longitudinal axis, q is rate-of-change of aircraft attitude angle, and θ is the aircraft attitude angle. The state space of HIMAT can be written as

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

The control inputs are the elevon and the canard. The measured variables are angle-of-attack and pitch angle. In this paper, the linearlized model is taken from [11], that is

$$A = \begin{bmatrix} -0.0226 & -36.6 & -18.9 & -32.1 \\ 0 & -1.9 & 0.983 & 0 \\ 0.0123 & -11.7 & -2.63 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \; B = \begin{bmatrix} 0 & 0 \\ -0.414 & 0 \\ -77.8 & 22.4 \\ 0 & 0 \end{bmatrix},$$
$$C = \begin{bmatrix} 0 & 57.3 & 0 & 0 \\ 0 & 0 & 0 & 57.3 \end{bmatrix}, \; D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

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