The Effects of Pressure Variation in Sliding Mode Controller with Optimized PID Sliding Surface

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Abstract. The high demands in the control of force and position implemented in diverse applications have led to the increasing usage of Electro-Hydraulic Actuator (EHA) system. However, the EHA system is commonly exposed to the parameter variations, disturbances, and uncertainties, which are caused by the changes in the operating conditions. Hence, this paper attempts to analyses the impact of changes during the operating condition and a robust control strategy is then formulated based on the control law of the Sliding Mode Control (SMC), where the design of the sliding surface is integrated with the Proportional-Integral-Derivative (PID) controller. Then, the Particle Swarm Optimization (PSO) technique has been utilized to seek for the optimum PID sliding surface parameters. The findings indicate that the proposed robust SMC with PSO-PID sliding surface is preserved to ensure the actuator robust and stable under the variation of the system operating condition, which produce 26% improvement in terms of its robustness characteristic.

Keywords: Electro-Hydraulic Actuator · Sliding Mode Control · PID sliding surface · Particle Swarm Optimization · Robustness analysis

1 Introduction

The power distribution by fluid power is historical and well acknowledge discipline, which is an energy transmitted through the medium of pressurized fluid. The growing of fluid power technology has fulfilled the demand in the control of an increased quantities of mass with higher precision and acceleration through the lowest power consumption implemented to various engineering applications.

In the areas of manufacturing assembly line, machining tools, and aerodynamic control, quick response with accurateness at the high power level are the crucial factors that yielding the integration of the electronic components into the hydraulic

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servomechanism. In the field of electronics, the data and information can be easily processed and transduced [1], while the demand in high force and high speed can be delivered by the hydraulic servomechanism [2]. Thus, an integration that absorbs the features of both electronic and hydraulic servomechanism forming the Electro-Hydraulic Actuator (EHA) system, which produces more reliable, more efficient, and better performance that could meet one expectations [3]. However, the EHA system is highly nonlinear, time varying, and have many uncertainties in nature, which resulting in more challenging tasks in the controller design and the development of an accurate dynamic model. These issues occurred in the hydraulic system have been discovered by many researchers in the past several decades [4–8].

In the study of [9], they have emphasized that various types of robust and adaptive control strategies have been developed over the years to overcome the issues occurred in this system [10, 11]. The issues discovered in the past including valve overlapping [12], directional changes in valve opening [13], and the non-smooth nonlinearities [14] during the control input saturation. However, in the recent study by [15], they have underlined that the unstructured uncertainties are always exist in the hydraulic system, which have become a main obstacle in the development of the controller design, especially in the development of high-accuracy tracking control. Further encouragement has been given to academia and researchers in the development of the high-accuracy control strategy in order to enhance the hydraulic actuator performance.

In the past, numerous control approaches have been suggested to enhance the tracking capabilities of the hydraulic actuator. These control strategies may be loosely classified into linear control, nonlinear control, and intelligent control approaches [16]. However, a linear control strategies might be facing the robustness issues towards the significant variations in the system's parameter. In addition, in the control of the positioning tracking in the EHA system, although the intelligent techniques have presented acceptable performances, but a potential stability problem has been governed by these techniques [17]. Generally, the discussions on the stability factors in the controller design were ignored. Therefore, in order to overcome the stability issues, and increase the robustness towards the changes occurred in the system, the nonlinear control strategy, which is SMC robust control that using different approaches is found to be potential in dealing with these issues [18–25].

Through the study of the literature, it is realized that recent trend has shifted towards the computational tuning method to dealing with the issues existed in the EHA system. With the evolutionary, high efficient, and cost effective computational optimization algorithm, extensive control issues have been solved and improved particularly in the engineering apparatus. The rapid improvements in computational technologies simultaneously enhance the robust control approaches, which has been implemented in the EHA system. In the metaheuristic optimization techniques such as PSO, GA, and DE, the PSO was found to be potential in solving the positioning tracking control issue especially in the EHA system employed to various types of controller [26–31].

Therefore, in this study, an evaluation regarding the robustness analysis of the proposed SMC with PID sliding surface control strategy implemented to the EHA system has been carried out. The mathematical modelling of the EHA system, and also the derivation of the PID sliding surface will be adopted from [32]. Then, the PSO algorithm will be employed to obtain the other variables value of the PID controller, which was later integrated into the sliding surface of SMC controller. Finally, the simulation exercises are presented to illustrate the effectiveness of the proposed method.

2 Physical Model of EHA System in Simulink

The development of the physical model for the EHA system will be done by using MATLAB/Simulink 2013 software. In this study, the EHA system will be first modelled according to the mathematical modelling of the EHA system based on the first principles of the physical law as discussed in [32]. After the formation of EHA system, the sliding mode controller will be integrated with the PID sliding surface, which is particularly applied to control the displacement of the EHA system. Figure 1 indicates the Simulink block diagram EHA system implemented in this study.

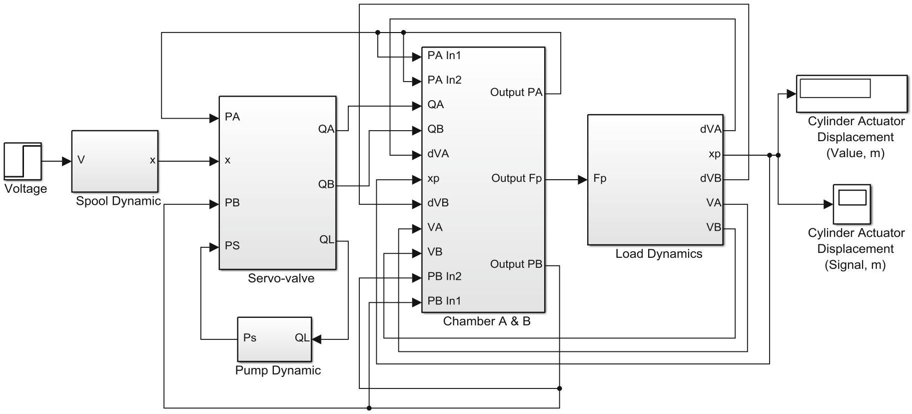

Fig. 1. Simulink block diagram of the EHA system

2.1 Integration of PSO to the SMC with PID Sliding Surface

PSO is an algorithm based on the inspiration of a swarming behaviour of insects, animals, or even humans, which was introduced by James Kennedy and Russell C. Eberhart, who is a social psychologist and an electrical engineer at America in 1995. A group of agents known as particles, which is the composition of insect like ants, animal like birds, or humans that randomly walking around the wide range area to looking for food, treasure, or resources supposedly. The searching activity will always start from random search, then these creatures will communicate and share their current best information among each other. Finally, the summarized or computed current best information will be formed into a global best information, which will usually end up with a quality global best information.

Two important operators that will manipulate in the searching process are the velocity and position update. During the searching process, each of the current particles will accelerate to the new position or searching point, by according to the velocity value that composed of previous velocity and position information. The general velocity and position update have a formation of the equations as denoted below [33]:

$$v_{id}^{k+1} = v_{id}^{k} + c_1 rand_1^k (pbest_{id}^k - s_{id}^k) + c_2 rand_2^k (gbest_{id}^k - s_{id}^k) \tag{1}$$

$$s_{id}^{k+1} = s_{id}^{k} + v_{id}^{k+1} \tag{2}$$

The description of the equation above is tabulated in Table 1. The searching process will be repeated until the stopping condition and criteria is met. The condition and criteria included fixed maximum for the number of iterations, or the error measurement of the function approximate or reached the minimum.

Table 1. List of terms and descriptions for the general equation of PSO

Terms	Descriptions
i	The value of particle or agent, where i = 1, 2, 3, …, n
d	The dimension of the problem, where d = 1, 2, 3, …, n
k	The iteration of particle or agent, where k = 1, 2, 3, …, n
$k + 1$	The future iteration of particle or agent
v	The velocity of the algorithm
s	The searching point of the algorithm
$c_{1/2}$	c_1 represents the self-coefficient, c_2 represents the group/swarm-coefficient
$rand_{1/2}$	$rand$ = random numbers ranged from 0 to 1 $rand_1$ is the random value of self-coefficient $rand_2$ is the random value of group-coefficient
pbest	The particle's self or personal best value
gbest	The particle's group/swarm or global best value

In the development of the PSO algorithm in this study, the procedure of the development has been summarized into the flow chart as depicted in Fig. 2. The searching process will be started by a random distribution of the particle's velocity and position in the wide range area that consists of local and global region or problem space. The randomly distributed particles will then occupy the problem space and perform the execution in searching for the best solution, or in other terms known as fitness in the local region. Each of the particles will keep tracking their best coordinates, which were associated with the current velocity and the achieved current best fitness value so far that was known as local best, *lbest* value. The fitness value will be stored in the memory array with the given name of personal best, *pbest* value. Through the repetition of the searching process, the best *pbest* value among each of the particles will be judged as the global best, *gbest* value. Commonly, the development of the PSO algorithm as depicted in the flowchart in Fig. 2 will follow the procedures as stated below:

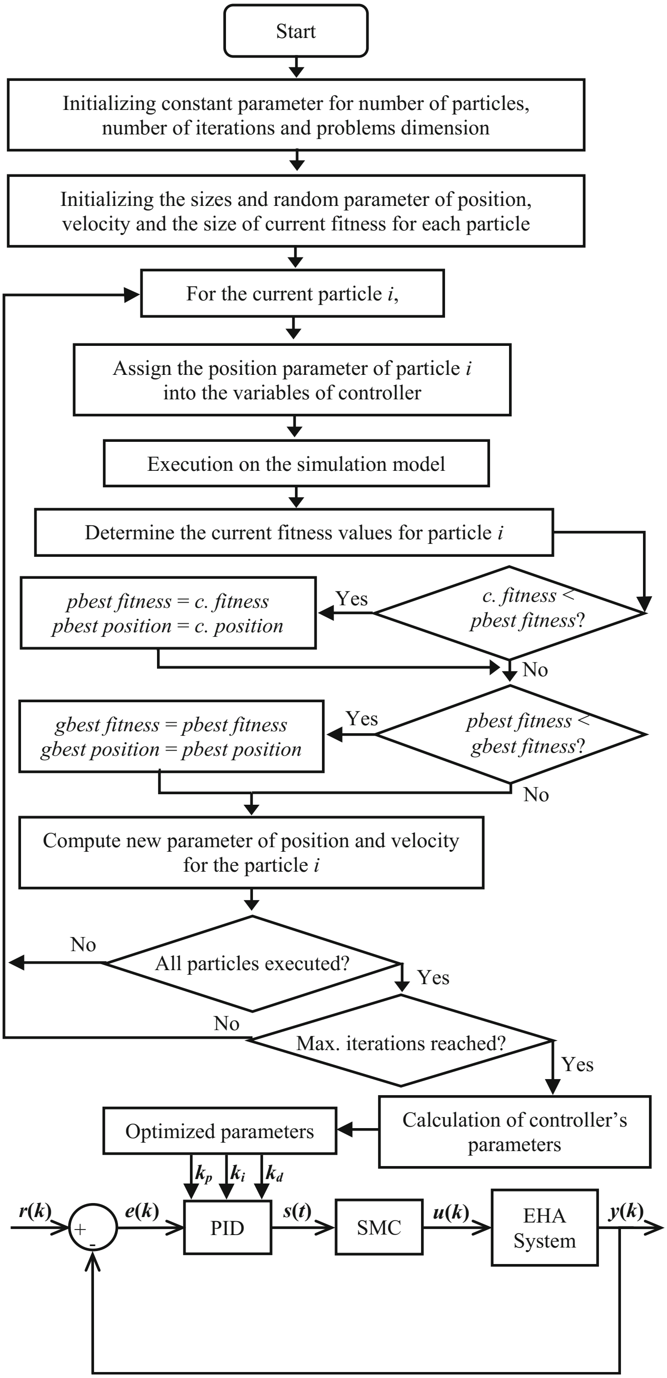

Fig. 2. Flow chart and block diagram of proposed control strategies

i. Initializing a constant value for the sizes of the swarm, numbers of iteration, and problems dimension (*d*),
ii. Initializing swarm of particles in an array according to the *d* with random set of velocities and positions,
iii. For each of the particles, start the execution in searching for the fitness information in the *d* variable,
iv. Evaluate the fitness information for the current particle with the *pbest* particle. If the current particle solution is better than *pbest* particle, *pbest* value will be replaced by the current particle value, and the location of the current particle will be transformed into the *pbest* location in the d dimension,
v. Compare the current fitness information with overall swarm fitness information. If the current fitness value is better than *gbest* fitness value, replacing the *gbest* fitness value with current fitness value,
vi. Updating the velocity and position information according to the Eqs. (1) and (2) respectively,
vii. Repeat the loop to Step iii until the stopping criterion is met.

where $r(k)$ denotes the reference or desired input signal, $e(k)$ is the errors produced by the system, $s(t)$ represents the sliding surface of the SMC, $u(k)$ is the control signal of the SMC, and $y(k)$ is the output response of the EHA system.

With the assistance of PID controller on the sliding surface of the SMC, the control signal is expected to be reached to the desired point faster and smoother than the conventional SMC approach. Finally, the PSO algorithm will be used to obtained an optimal value for the PID sliding surface of the SMC, which will significantly improve the control performance and reduce the control effort as demonstrated in the coming chapter.

2.2 Robustness Index

The robustness test is conducted with the purpose to evaluate the robustness of the developed controller. Generally, robustness test for EHA system is conducted by reducing or increasing the supply pressure to represent the parameter variations [3, 28]. The investigations under the changes of the operating conditions and robustness study of the implemented controllers are crucial in the control performance assessment. Thus, a practical way to measure the robustness of the controllers is to determine the Root Mean Square Error (RMSE) obtained for the nominal operating condition ($RMSE_{nom}$) and the changed of plant parameters ($RMSE_{var}$) condition. The quantitative measure which known as the robustness index (*RI*) for a reference trajectory (*RT*), under a particular plant condition over a tracking process of period (*T*) is given as:

$$RI(T,RT) = \frac{|RMSE_{nom} - RMSE_{\mathrm{var}}|}{RMSE_{nom}} \tag{3}$$

The robustness index has been used in the comparative evaluation on the tracking performance of the EHA system by using the robust control scheme. This metric will show the capability of the proposed control scheme for the system under the disturbances and uncertainties circumstances.

3 Results and Discussion

Before the evaluation of the proposed method, the step reference input signal has been first employed to the EHA system that is operated without the assistant of the controller in order to observe the capability of the proposed control approach. The system has been connected in two different circumstances, which are open-loop and closed-loop, and executed in 60 s as demonstrated in Fig. 3.

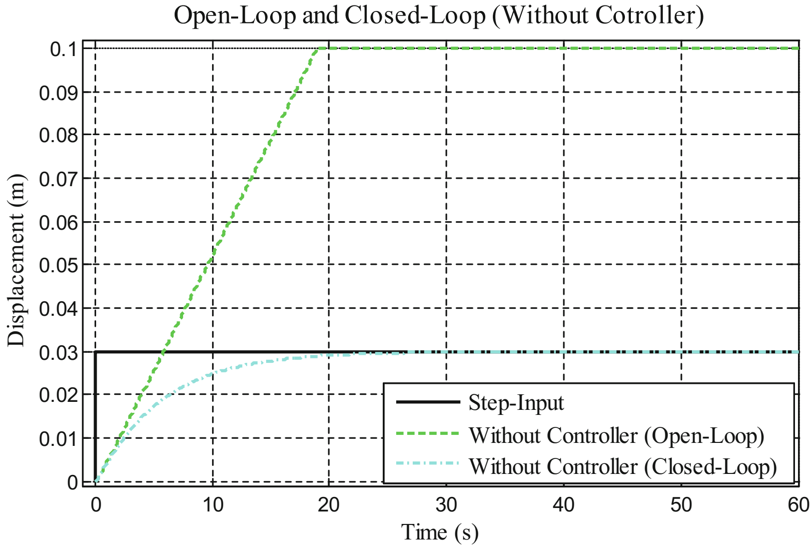

Fig. 3. The response of the EHA system in open-loop and closed-loop without the assistant of the controller (Color figure online)

As clearly depicted in Fig. 3, the EHA system will be operated in a static way, where the hydraulic actuator will be extended to the maximum stroke of the cylinder without follow the step reference signal that has been fed to the system as represented in green dash line. The times taken to reach to the maximum stroke are almost 18 to 20 s. When the system is connected in a closed-loop circumstance, the actuator has been clearly followed the desired trajectory. However, the actuator took a very long time to reach to the desired trajectory, which are between 20 to 25 s. Thus, in can be inferred that the assistant of the controller is needed in order to achieve our desired performance, which including efficiency, accuracy, fast and stable response.

The controller that is capable to perform without sacrificing the limitation of the EHA system is another issue to be concerned. Therefore, the controller robustness analysis based on the step input reference signal has been conducted. As the discussion that has been made in the article [34], the effect occurred during the changes in the EHA system parameters has been carefully evaluated. It is observed in that study, the most influential parameters are including the servo-valve gain (K), supply pressure (P_s), and the total moving mass (M_p). The Ps has been chosen in the evaluation of the controller robustness characteristic due to its practical application to the real-time EHA system. It is also observed in that study, the variation of ±25%, and ±75% doesn't contribute much to the effect occurred in the EHA system, but only at the settling time of the system. In order to assess the performance of the control scheme with the deduction of 25%, 50%, and 75% on the P_s, the parameters of the PSO algorithm have been applied to the PID controller, and the PID sliding surface of the SMC, which produced the performances as shown in Figs. 4 and 5 respectively.

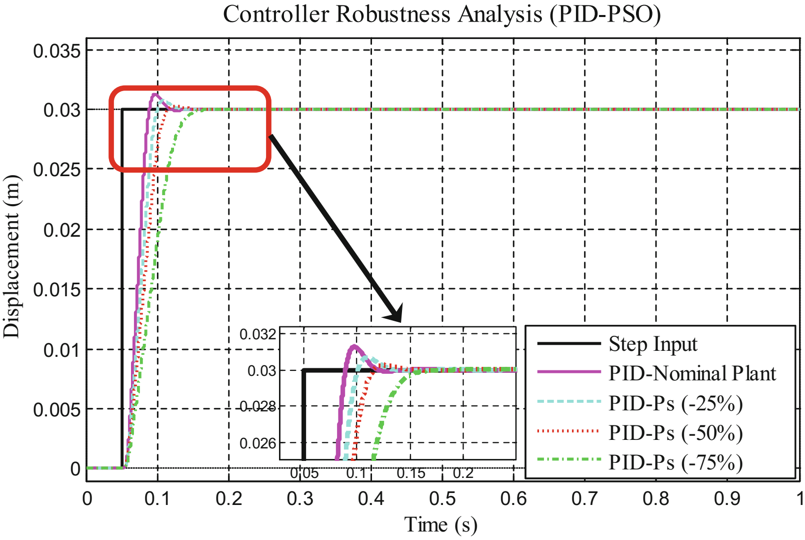

Fig. 4. Robustness analysis based on PID controller

Hence, the variation on the P_s with the deduction of 50% from the nominal supply pressure has been set in the scope of the study, which represent the changes occurred in the system parameters, that will be used to analyse the controller robustness characteristics. Figure 6 depicts the response of the SMC and the PID controller. The PID-PSO applied to the nominal plant is represented in red colour dash-dot line, and the PID-PSO applied to the varied plant denotes in green colour dot line, while the SMC-PID-PSO applied to the nominal plant demonstrated in magenta colour dash line, and the SMC-PID-PSO implemented to the varied plant indicated in blue colour solid line.

As clearly shown in the zoomed-in figure in Fig. 6. It is clearly seen that the response produced by the PID-PSO applied to the nominal EHA plant generated slower rise time and settling time depicted in red colour dash-dot line as compared to the SMC-PID-PSO that illustrated in magenta colour dash line. When the supply pressure

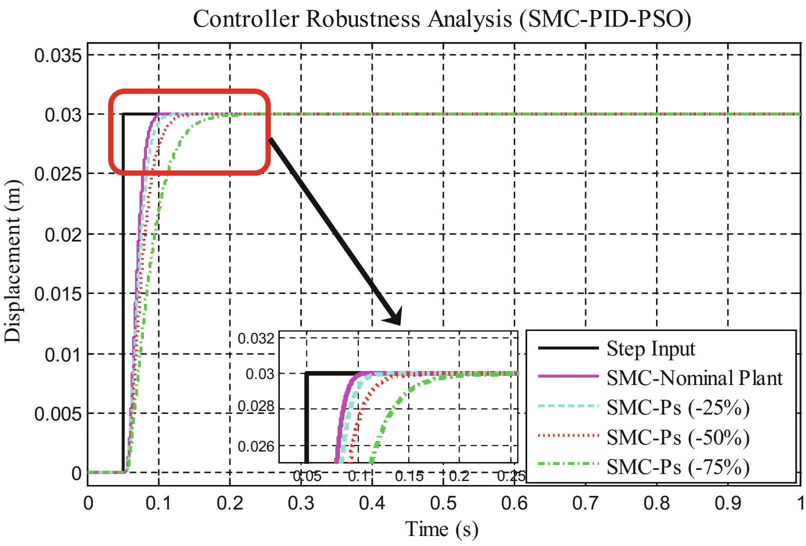

Fig. 5. Robustness analysis based on SMC

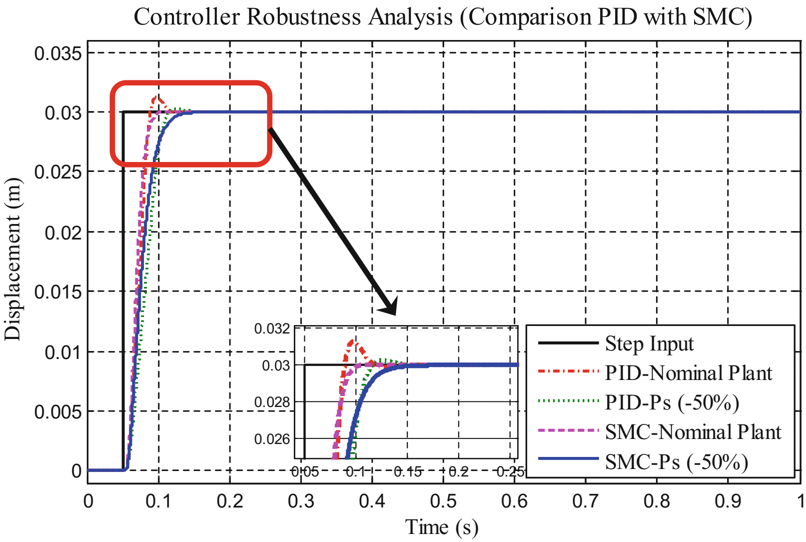

Fig. 6. Controllers robustness analysis implemented in nominal plant and pressure variation for the EHA system (Color figure online)

has been varied for the purpose of controller robustness analysis, the rise time and settling time of PID-PSO even worse as represented in green colour dot line, while the response of the SMC-PID-PSO result in better performance as shown in blue colour solid line.

To produce a much clearer view in the robustness characteristic of the SMC and the PID controller when employed to the nominal EHA plant and the variation on the EHA supply pressure, Table 2 tabulated the RMSE analysis and the robustness index for both controllers respectively. It can be seen in Table 2, the robustness index generated by SMC is smaller as compared to the PID controller, which indicated that the SMC controller has a better robustness characteristic compared to the PID controller when there is a change in system parameters. As compared with the PID controller, 26% improvement of the robustness characteristic has been obtained when the SMC is implemented to the EHA system. This phenomenon is crucial when dealing with the systems that have problems such as disturbances, nonlinearities, and uncertainties since these problems are hard to be captured and handle in the real world.

Table 2. Robustness analysis for SMC and PID controller

Controller	Plant	Controller robustness analysis	
		RMSE	Robustness index value
PID-PSO	Nominal	3.9671×10^{-3}	0.1629
	P_s, (−50%)	4.6132×10^{-3}	
SMC-PID-PSO	Nominal	3.7549×10^{-3}	0.1212
	P_s, (−50%)	4.2099×10^{-3}	

4 Conclusion

This paper has presented an optimization on the developed controller variables, which is the sliding mode controller based on PID sliding surface structure, implemented in the position tracking control of the EHA system. It is well-known that the EHA system is commonly exposed to the parameter variations, disturbances, and uncertainties. Therefore, an optimization is required to reduce the controller's effort and improve its robustness towards the changes and uncertain operating conditions. Compared to the conventional PID controller, the proposed robust control strategy outperforms without sacrificing the limitation of the EHA system, which was analysed in term of the robustness quality and the positioning tracking accuracy. In conclusion, it is demonstrated that the proposed robust SMC with the optimized PID sliding surface is preserved to keep the actuator robust and stable under the variation of the system operating condition.

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