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Optimized Design of Wide-Area PSS for Damping of Inter-Area Oscillation

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***Abstract*—In this paper a genetic algorithm based wide area power system stabilizer (PSS) in a multi machine power system for damping of low frequency inter-area oscillations has been presented. The wide area PSS is consists of two stages, the input of one stage is a local signal and the input of other is a global signal. To select the most effective stabilizing signals and the location of controller, Geometric measure of controllability and observability is used. The most effective input signal found is the tie line active power flow deviation. Time domain based objective function is minimized, in which deviation in the oscillatory rotor speed of generator is involved so that the stability performance of the system is improved. Two area - four machine systems have been used as a test system here.**

In this work,

***Index Terms*—Wide-area PSS, low frequency inter-area oscillation, genetic algorithm, geometric measure of controllability and observability.**

I. INTRODUCTION

The stability of electro-mechanical oscillations in a large interconnected power system is necessary for reliable operation of a power system. The oscillations of a single generator or single plant with respect to the rest of the power system are known as local modes, while those linked with groups of generators in one area swinging against a group of generators in another area are known as inter-area modes [1]. The inter-area modes of oscillations are mainly caused due to bulk amount of power transmission over a long distance through relatively weak tie lines and because of using exciters with high gain [2]. These oscillations results into instability in a large scale power system.

Since 1990s, Synchro-phasor based phasor measurement units (PMUs) have been used for getting global signals in wide area damping controllers. In conventional approach, these oscillations are damped out using Conventional Power System Stabilizer, which is a part of the generator’s excitation control system. Using generator’s excitation control system which employs local signals as inputs, inter-area oscillations cannot be effectively damped out. A few limitations are there such as : (i) Generator controllers lack overall surveillance and observation of inter-area network .(ii) At a nominal operating point, the system model is linearized and it is valid only near to the operating point [4]. Due to continuous change in load, operating point has continuous variation. Many global signals are there and some of them are the difference between two generator speed deviation, active power flow deviations, etc. It is found that if the global signals received from remote areas are used in wide-area damping controller, then the system dynamic performance can be improved with respect to the inter-area oscillations [3]. Geometric measures of controllability /observability can be used to select a suitable input signal and location [4]. One of the effective global signal for inter-area oscillations is deviation in tie line active power flow [3-5]. The PMUs which are connected at different locations in the wide-area network measure dynamic data of a power system such as voltage, current, load angle and frequency [6].

Here, a two-stage global signal based wide-area PSS controller has been used [4]. This paper implements the genetic algorithm (GA) based optimization technique for optimizing parameters of the wide-area PSS [7-9]. The GA refers to random search algorithm which works on principle of mechanics of natural selection and natural genetics. GA uses iterative procedures that maintain population of candidate solutions to optimize a fitness function. The first stage of control is obtained from a local signal and is designed to damp out local mode of oscillations effectively caused mainly due to the local disturbances. The second stage of control is obtained from a global signal (tie line active power flows) to damp out poorly damped inter-area modes of oscillations. Genetic algorithm technique is free from complexity of the performance index that we have considered.

The remaining portion of this paper is described below. In section II, the test system under study is described briefly. in section III, Power system modeling and its linearization has been described. In section IV, an overview of Genetic Algorithm (GA) and problem formulation , Selection of input signal and control location, designing of local PSSs, designing of proposed two-stage wide-area PSS has been explained in the proposed methodologies. In the Section V ,the simulation results and discussion, Conclusion and references taken are presented .

II. MODELLING OF POWER SYSTEM

Oscillations having frequencies range from less than 1 Hz to 3 Hz other than those with sub-synchronous resonance

(SSR) are called as low frequency electro-mechanical oscillations. Behaviour of a large scale power system is expressed in terms of a set of non-linear differential and algebraic (DAE) equations. These equations can be linearized around the equilibrium operating point and a set of linear DAE is obtained as given below [21]:

$$\dot{x} = f(x, z, u) \tag{1}$$
$$y = h(x, z\ u) \tag{2}$$

The notation $x \epsilon R^n, z \epsilon R^m$, $u \epsilon R^p$ and $y \epsilon R^q$ denotes the vectors of state variables, algebraic variables, inputs and outputs respectively. After linearizing above Equations (1) & (2) around the equilibrium point $\{x_{o,} z_{o,} u_o\}$ results into the following equations:

$$\Delta\dot{x} = A\Delta x + B\Delta u \tag{3}$$
$$\Delta y = C\Delta x + D\Delta u \tag{4}$$

Where, A, B, C and D are the matrices of partial derivatives evaluated at equilibrium $(x_{o,} z_{o,} u_o)$. These linearized DAE model of a power system can be directly applied for standard linear analysis.

III. Selecting Stabilizing Signal and Control Location

In this paper geometric measure based controllability/observability has been applied for selection of feedback signal and optimal control location of the WAPSS [7, 14]. In this paper only line active power flow deviation (MW) has been taken as the input signal to the wide area signal based controller and the voltage stabilizing input signal to the generator exciter is the output of controller. A joint controllability/observability index has been used for the selection of the stabilizing signal. After linearization around a given operating condition, algebraic variables has been eliminated and, the state-space model of the system is given by:

$$\dot{x} = Ax + Bu \tag{5}$$
$$y = Cx \tag{6}$$

Where x is the n x 1 state vector; y is the p x 1 measured output vector; u is the m x 1 input vector whose entries are control signals sent out by WAPSS; A (n x n), B (n x M) and c (P x n) are the state, input and output matrices respectively.
Let matrix A has n distinct Eigen values $(\lambda_i, i = 1, \ldots\ldots, n)$ and assume that the matrix 'A' has φ_i *and* ψ_i as the right and left Eigen vectors respectively, associated with an i^{th} mode of oscillation. Considering independent orthogonal relationship between left and right Eigen vectors, then the controllability index (COI_j) and observability index (OBI_k) for the i^{th} mode can be defined as [7]:

$$COI_j = \cos\left(\theta(\psi_i, B_j)\right) = \frac{|B_j^T \psi_i|}{\left||C_j|\right|\,||\varphi_i||} \tag{7}$$

$$OBJ_k = \cos(\theta(\varphi_i, C_k)) = \frac{C_j \varphi_i}{\left||C_j|\right|\,||\varphi_i||} \tag{8}$$

Where B_j is the j^{th}column of matrix B and C_k is the k^{th} row of the matrix C. |Z| and ||Z|| are the modulus and Euclidean norm of Z, respectively. $\theta(\psi_i, B_j)$ is the geometric angle between input vector j and the left Eigen vector, while $\theta(\varphi_i, C_k)$ is the geometrical angle between the output vector K and the i^{th} right eigen vector. The joint controllability/observability index can be written as:

$$Joint\_index_{jk} = COI_j\ X\ OBI_k \tag{9}$$

In the proposed design procedure, only few measurements with highest observability of inter-area modes are selected as stabilizing input signal and only a few generators having highest controllability of those modes are chosen as optimal control location.

IV. Design of Proposed Two-Stage Wide Area PSS

To enhance the damping of poorly damped local and inter-area modes of oscillation is the objective of this proposed two-stage controller. The control signal used here is consists of two components; the first control signal is obtained from the local generator speed deviation (first stage controller) and the second control signal is obtained from the remote signal or global signal or a wide-area signal i.e line active power flow deviation (second stage controller).

A. Design of First-Stage Controller, PSS(L)

The PSS(L) is connected at each machine having a poorly damped local mode. The detail design of the PSS(L) is followed from [8]. The parameters of the lead-lag network are expressed as:

$$H_{PSS(L)}(s) = K_A \frac{ST_{WA}}{1 + ST_{WA}} \left[\frac{1 + ST_{1A}}{1 + ST_{2A}}\right]^n \tag{10}$$

Where, T_{WA} is the washout filter time constant and its value is taken in the range of 1 to 20 seconds , *n* is known as the number of lead-lag blocks or compensating blocks. and T_{2A}, T_{1A} are lead-lag compensating network time constants [4]. To obtain the value of gain K_A ,GA optimization technique is used.

B. Design of PSS(G) by Using Tie-Line Power

The PSS(G) are connected to the selected generator in addition to the PSS(L).The transfer function of the PSS(G) is as below :

$$H_{PSS(G)}(s) = K_B \frac{ST_{WB}}{1 + ST_{WB}} \left[\frac{1 + ST_{1B}}{1 + ST_{2B}}\right]^n \tag{11}$$

Where T_{WB} denotes washout time constant (usually 1 to 20 seconds) and T_{1B}, T_{2B} represents the first and second stage lead-lag compensating network time constants [3]. In this case, ω_g is the frequency of the inter-area mode in rad/second. The value of gain K_B is obtained by using GA optimization technique. Figure-1, shows the block diagram of WAPSS with two-stage feedback [10] .Then the total control signal is written as :

$$V_S = H_{PSS(L)} * \Delta\omega + H_{PSS(G)} * \Delta P_{tie} \tag{12}$$

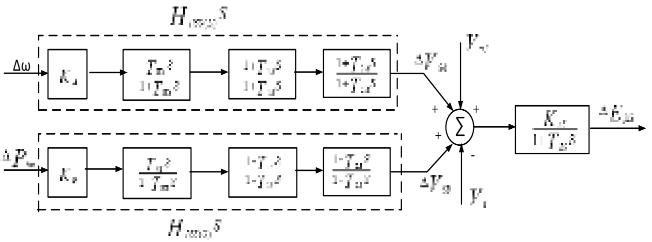

Figure.1 The block diagram of WAPSS with two-stage feedback

C. *Genetic Algorithm Technique*

The genetic algorithm technique is based on the "survival of the fittest" which is derived from Darwinian Theory. It is basically a random search algorithm based on the mechanics of natural selection and natural genetics. It is. It mimics or imitates or simulates the process of "evolution". Evolution is an optimizing process, i.e. successive generations are becoming better and better. Each generation is like iteration in numerical methods.

1. Objective Function Criterion

In this case of the given lead-lag PSS structure, we have taken the time constant T_{SN}=15 milliseconds and washout time constant T_W=10 seconds. We are to find out the controller gain K_{PSS} and the compensating network time constants T_1, T_2, T_3 and T_4 .

In the given case, for analysis 11- bus 4 -machine MMPS (multi-machine power system) power system, for the objective, an integral time absolute error of the speed signals corresponding to the local and inter-area modes of oscillations is taken as the objective function.

The objective function of the given 11- bus 4 -machine MMPS is expressed as:

$$OBJ_i = \int_{t=0}^{t=t_{sim}} \left(\sum \Delta\omega_L + \sum \Delta\omega_I\right) t\, dt \qquad (13)$$

Where, $\Delta\omega_L$ and $\Delta\omega_I$ are the speed deviations of the inter-area and local modes of oscillations respectively and t_{sim} is the time range of the simulation. In the given two area four machine system study the local mode $\Delta\omega_L$ is $[(\omega_1 - \omega_2) + (\omega_3 - \omega_4)]$ and the inter-area mode $\Delta\omega_I$ is $[(\omega_1 - \omega_3) + (\omega_1 - \omega_4) + (\omega_2 - \omega_3) + (\omega_2 - \omega_4)]$, where $\omega_1, \omega_2, \omega_3$ and ω_4 are the speed deviations of machines 1,2,3 and 4 respectively.

2. Design Constraint in the Investigated Problem

The optimum design problem which we have considered can be derived in terms of the following optimization problem:

Minimize J

Subjected to $K_{PSS}^{min} \leq K_{PSS} \leq K_{PSS}^{max}$

$$T_1^{min} \leq T_1 \leq T_1^{max}$$
$$T_2^{min} \leq T_2 \leq T_2^{max}$$
$$T_3^{min} \leq T_3 \leq T_3^{max}$$
$$T_4^{min} \leq T_4 \leq T_4^{max}$$

V. IMPLEMENTATION AND RESULTS

A. *The Test System Adapted*

The proposed GA(genetic algorithm) optimized wide-area PSS has been applied on the Kundur's 2 area 4 machine power system. The 4 machine 11 bus system, taken for study in this work is shown as in Fig. 2. The parameters considered here is taken from reference [1]. The loads in the system are assumed as constant impedance type. To damp out local modes of oscillations and inter-area modes of oscillation each selected generators are provided with two-stage wide-area PSS (WAPSS) which are connected to the input of the AVR.

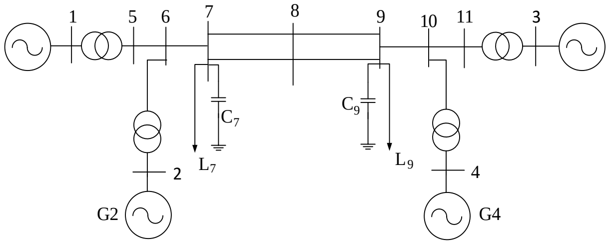

Figure.2 Kundur's 2 area 4 machine system

B. *Small Signal Stability Analysis*

Without considering PSS in none of the generators,the small signal stability analysis of the 4 machine 11 bus power system is performed. Thus the critical inter-area Eigen value or critical mode of the system is identified which is given in Table-1 and this is the only one inter-area mode of oscillation, of 0.6308 Hz present in the system.

TABLE I: CRITICAL MODE OF 4 MACHINE 11 BUS SYSTEM

Mode no.	Eigen value	Damping ratio	Frequency
Mode 1	0.0497 $\pm 4.0137i$	-0.0214	0.6388

C. *Wide-Area Signal Selection*

The method of geometric measures of controllability/observability is used for signal selection as described in section- III. After small signal stability analysis of the 4 machine 11 bus systems, a state-space object of the above system with input matrix as change in voltage reference at exciter and output matrix as change in line active power is formed and again the Eigen value analysis of the state-space object is done. Thus, the right and left Eigen vector for the mode of interest are calculated. Then by using the method of geometric measures of controllability/observability a normalized joint controllability/observability index has been developed which is given in Table II:

TABLE II NORMALIZED VALUE OF JOINT CONTROLLABILITY/OBSERVABILITY

Generators	$P_{6\text{-}7}$	$P_{7\text{-}8}$	$P_{8\text{-}9}$	$P_{9\text{-}10}$
G1	0.2827	0.7429	0.7363	0.3848
G2	0.3787	0.9938	0.9860	0.5147
G3	0.2853	0.7494	0.7428	0.3880
G4	0.3805	1.0000	0.9916	0.5174

From Table II, it can be observed that for tie-line power flow between 7 and 8, generator no.2 and 4 have the highest degree of controllability and observability. Hence as per the theory mentioned in section-III, it can be said that generator no.2 and 4 are most efficient generators to damp inter-area oscillations. Hence both the generators are most appropriate location for the installation of WAPSS. The stabilized signal to be used as wide-area control signal is the tie-line power flow between bus 7 and 8.

D. Application of GA

In order to get the optimization of equation-27, routines from genetic algorithm for optimization toolbox (GOAT) [19] are used. The optimal values of the WAPSS controller parameters obtained by the GA optimization technique are given in Table III and Table IV respectively.

TABLE III : RANGE OF WAPSS PARAMETERS FOR 4 MACHINE 11 BUS SYSTEM

Parameters	WAPSS-1		WAPSS-2	
	PSS(G)	PSS(L)	PSS(G)	PSS(L)
K_{PSS}	0.1-1	10-20	0.1-1	10-20
T_1	0.1-1	0.01-0.1	0.1-1	0.01-0.1
T_2	0.01-0.1	0.01-0.1	0.01-0.1	0.01-0.1
T_3	0.01-0.1	1-10	0.1-0.2	1-10
T_4	0.01-0.1	1-10	0.01-0.1	1-10

TABLE IV OPTIMIZED WAPSS PARAMETERS FOR 4 MACHINE 11 BUS SYSTEM

Parameters	WAPSS-1		WAPSS-2	
	PSS(G)	PSS(L)	PSS(G)	PSS(L)
K_{PSS}	0.1340	13.209	0.1277	15.4877
T_1	0.1	0.05	0.1	0.05
T_2	0.02	0.02	0.02	0.02
T_3	0.05	3	0.12	3
T_4	0.01	5.4	0.01	5.4

Then, in order to test the robustness of the proposed controller, the optimal value of the WAPSS controller parameters are again applied to the WAPSS controller with a three phase fault applied to the system for 8 cycles.

E. Simulation Results

The dynamic performance of the system was examined under two different cases i.e. small signal performance assessment and large signal performance and robustness assessment.

1. Small Signal Performance Assessments

To simulate the small-signal stability, a small disturbance of 5% magnitude pulse is applied for 12 cycles at voltage reference of G1 with a simulation time of 20 seconds. Under such circumstance, the response of the tie-line active power flow deviation, rotor speed deviation of G2, and change in rotor angle of G2 with respect to G4 are examined by considering the system without controller, with local controller and with the proposed GA optimized WAPSS controller. Fig.3,4,5 shows the responses of the tie-line active power flow deviations, rotor speed deviation of G2 and change in rotor angle of G2 with respect G4 respectively under small signal analysis.

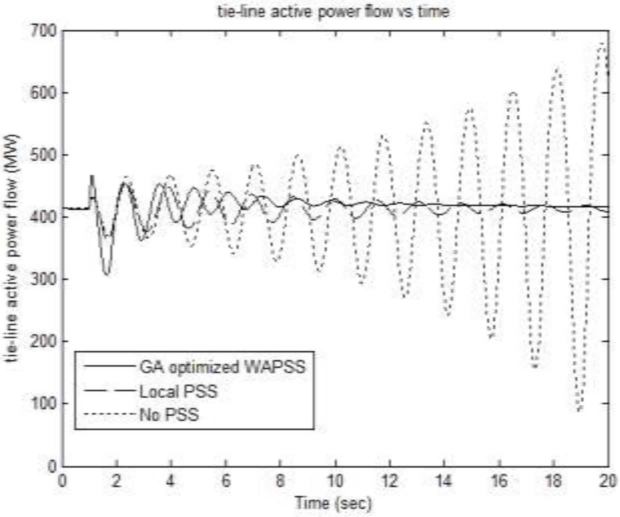

Figure.3 Response of tie-line active power flow deviation

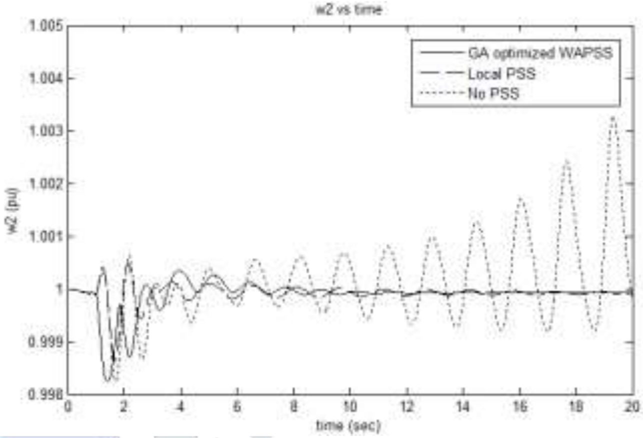

Figure.4 Response of rotor speed deviation of G2

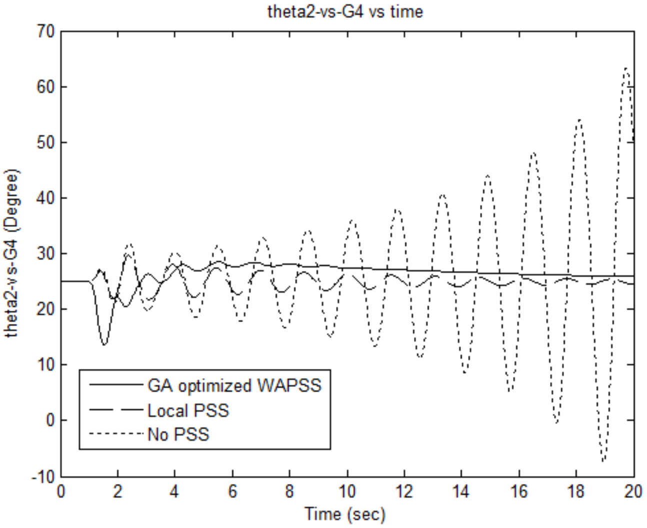

Figure.5 Response of change in rotor angle of G2 with respect to G4

From the above figures it is found that, under small signal analysis, when the proposed GA optimized WAPSS (shown by a solid line in above figures) are employed in the electrical power system, they have a much better inert-area oscillation damping performance as compared to a conventional PSS or local PSS.

2. *Large Signal Performance and Robustness Assessment*

To simulate the large signal closed loop system response, a 3-phase fault is applied at the mid-point of tie-line of the system for 8 cycles after 1 second from starting of simulation. Under such circumstance, the responses of the tie-line active power flow deviation, rotor speed deviation of G2 and change in rotor angle of G2 with respect to G4 are examined by considering the system without controller (No PSS), with conventional controller (local controller) and with GA optimized WAPSS and the corresponding results are shown in Fig.6,7,8 respectively.

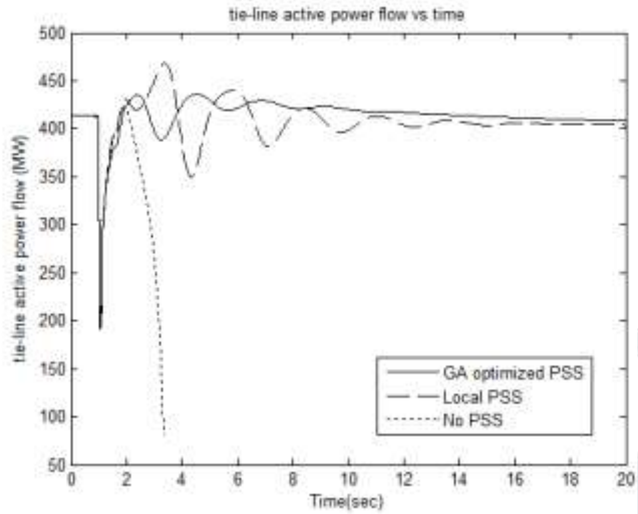

Figure.6 Response of tie-line active power flow deviation

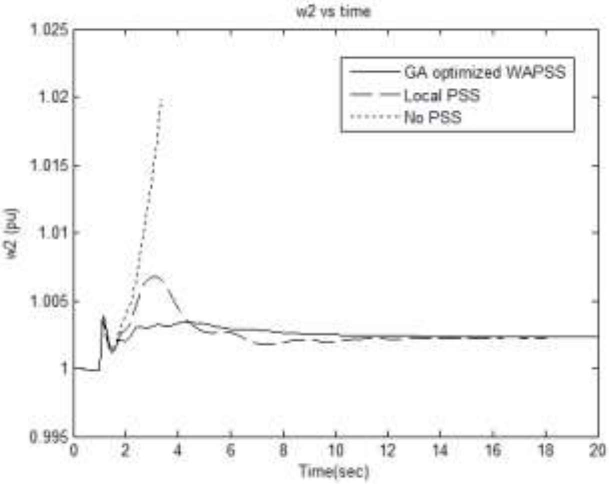

Figure.7 Response of rotor speed deviation of G2

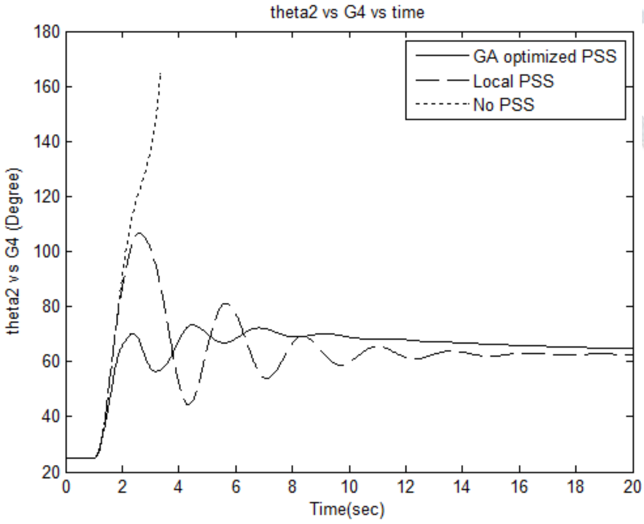

Figure.8 Response of change in rotor angle of G2 with respect to G4

A carefully noticing on the above results given in Fig.6,7,8, it is thus concluded that, when the proposed GA optimized WAPSS are employed in the electrical power system, they give a much better damping characteristics for the critical inter-area modes of oscillation and guarantee a much superior performance as compared to that when conventional PSSs are employed.

VI. CONCLUSION

This research investigated the wide-area damping control strategies to damp out the critical inter-area oscillations and enhance the stability of wide-area interconnected systems. Using the fast and flexible control techniques, a two-stage wide-area controller is developed by considering the lead-lag structured PSS with a proper signal selection method. The genetic algorithm technique has been implemented for the tuning or optimization of the proposed controller to make it robust to operate in different operating conditions.

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