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A robust FACTS based fuzzy control scheme for dynamic stabilization of generator station

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ABSTRACT

The paper presents a Flexible Alternating Current Transmission Systems (FACTS) based dynamic stabilization scheme using a modified series–parallel switched filter compensation (MSPFC). The proposed dynamic scheme is controlled by an Incremental Fuzzy Logic controller (MIFLC) to ensure fast response dynamic voltage stabilization and efficient energy utilization. The MIFLC employs a multi loop dynamic error driven time-descaled regulation to ensure the fast response of the dynamic controller. A second Weighted Modified PID controller with fixed gains is assessed with the proposed MIFLC controller. The modified control schemes are validated under normal and fault operating situations to ensure fast dynamic control, ac power quality, feeder loss reduction, efficient energy utilization and dynamic AC voltage stabilization regulation. The performance of the proposed controllers is assessed using statistical studies and qualitative comparison that prove the high ability of the proposed MIFLC compared with modified PID controller.

1. Introduction

Large Generation stations in Smart grid electric utility interfacing requires fast dynamic AC bus voltage stabilization. These fast-dynamic responses ensure efficient energy transfer as well as robust control actions. Recently, FACTS Technology is provided to ensure security, reliability, fault-tolerant operation and efficient energy utilization with assuring electrical power systems reliability [1,2]. The security and robustness issues of generation station in the integrated smart grid, efficient energy utilization, power quality, voltage regulation, security, reliability and dynamic voltage stability of the utility grid are now emerging as key performance indices. Low power quality problem is resulted due to the variations in load bus voltages, stressed load currents and large frequency deviations and equipment malfunction/failure [3].

Recently, the continuous developments in Power Electronic Converters and active filters with fast acting Intelligent Control Strategies using AI, Meta Heuristic and Intelligent Controllers in smart grid environment create situations of increased security, reliability, stability and energy efficiency. The most important issue in terms of energy utilization in smart grid is that the control of real power flow. Thus, controlling of how and where real power flows on the network is of critical significance, and is the essential principle behind the comprehension of smart electricity market. Congested transmission grids limit system reliability and pressure the ability of low-cost generators to provide interested customers with low-cost power. FACTS devices are investigated as stabilization, energy management and power flow control in Electric Utility Grid including transmission and distribution systems to increase transmission line power transfer and relieve congestion and transmission losses. Power flow and voltage control employed by FACTS devices are essential tasks for smart grid applications [4].

The fast-acting switched filters and capacitive compensation developed FACTS devices can be utilized as power filters and reactive compensation devices. During fault and sudden load changes, several power quality problems are raised such as voltage imbalances, waveform distortion, voltage fluctuation lead to shorage in the grid power quality [5]. By using SPWM-switched complementary switched capacitive banks, the power quality of the electric

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energy can be enhanced. The power quality issues are produced by nonlinearities and solid-state switching devices such as adjustable speed drives, power switching, and converters normally change the nature of loads and contribute to mushrooming nonlinearity of such loads [6].

Power filters with modified switched/modulated capacitive banks for combined power factor correction, power quality enhancement and transmission loss reduction are normally integrated for smart grid systems that fed by PV, wind and other renewable energy sources [7–11]. Ref. [7], with the aim of efficient energy utilisation, a robust FACTS PV-smart grid interface scheme was proposed. In [8], an adequate allocation of Energy Resources with the same aim in [7] is developed for Active Distribution Networks that have the power electronic switches called e Soft Open Points. The authors in [9,10] presented a general framework to incorporate one of the FACTS devices called TCSC devices into optimal power flow problem for achieving technical and economic benefits in power systems. The smart demand response procedure for efficient dealing with large population regime was presented in [11].

Sample of application that reported in the literature in smart grid environment such as adaptive fault identification and classification methodology for transmission systems in [12–15] and DC microgrid [16]. Solving the voltage fluctuations in the existence of renewable energy resources in smart distribution systems was carried out in [17]. In this work, the main aim is to minimize the voltage fluctuation resulted from increased levels of renewable energy sources and their uncertainty in smart distribution systems. Another issue is the optimal energy management considering economical operation of microgrids that was presented in [18,19], VAR compensation in hybrid AC/DC networks in [20] and controlling voltage profile with remotely allocation of controlled switches in [21] and by using soft open points in [8].

Conventional/Classical proportional-integral-derivative (PID) control scheme is used due to simplicity for design and flexibility in gain tuning and optimization using the Ziegler-Nichols, analytical, optimal and pole placement methods. The optimized gain parameters can be adjusted using heuristic/soft computing methods such as Tabu Search (TS) [22], Particle Swarm Optimization (PSO) [23], Genetic Algorithms (GA) [24], hierarchical fuzzy controllers for an astronomical telescope tracking [25], and ant colony optimization algorithms [26]. However, PID controllers are not expected to work well in nonlinear systems, higher order and/or time delayed linear systems [27]. A fuzzy logic technology and several methods are integrated for different applications in power system [28–34] due its ability to fine tuning of control variables The fuzzy and ANFIS based controllers were proposed for controlling the operation of two interconnected combined cycle gas turbine in [28]. The performance of grid connected PMSG-based wind turbine was enhanced by the adaptive fuzzy logic control strategy in Ref. [29] and was enhanced by considering hybrid ANFIS-GA-algorithm in [30]. In [31], the operation and control of HVDV stations was managed by combined p-norm and adaptive fuzzy controller. In [32], a proposed fuzzy based controller was presented for assuring the autonomous operation of voltage source converter of distributed generation systems. On the other hand, Fuzzy Logic Controllers (FLC) can be more flexible tool for dealing with system parameter-uncertainties and nonlinearity in the system and load excursions [33,34].

Moreover, several studies were suggested including both modified FLC and PID subjects as well. FLC is used for search adaptation of the conventional PID controller [35–38] whereas the FLC consider the error signal and the first derivative of error to optimize the controller gains. The concept of multi loop dynamic error driven decoupled, descaled controller is fully implemented and discussed [35]. The first dynamic tracking regulator *A* includes three decoupled and descaled loops. The first loop tracks the AC bus voltage reference whereas the second and third loops for stabilizing current excursions and limit generator power excursions, respectively. Therefore, only the inner part of this control block will be discussed to explain the applicability of the multi regulator decoupled time descaled Tri- multi loop PID controller and MIFLC in [37] and [38].

The salient features of the current work can be summarized as:

- A dynamic stabilization scheme using a modified series–parallel switched filter compensation (MSPFC) is proposed.
- The proposed novel dual action series - parallel modulated/switched filter act as a combined foyer - Series/Parallel capacitive compensation scheme with adjusted duty - cycle ratio that is dynamically modulated by the novel MIFLC controller.
- The MSPFC is modulated by PWM-switched Power Filter-Capacitor Compensator.
- Two control schemes based on multi-loop dynamic error driven and optimized-coordinated decoupled/descaled regulation scheme are proposed. The first is WMPID controller with fixed gain structure for each regulator. The second is the MIFLC used based on the global error and its rate of change of error as input variables.
- The modified control schemes are validated under normal and fault operating situations.
- Statistical assessment of the controller performance is carried out for different operating conditions

The rest sections of the paper are organized as follows: Section 2 presents the proposed methodology and the proposed structure of the controllers. Section 3 presents the digital simulation results associated with the discussion on the obtained results. The outcome of the current work is summarized in Section 4.

2. Methodology

2.1. Series-parallel-modulated switched power filter compensator

The FACTS Based, PWM-Switched dual-modulated switched power filter compensator is a complementary switched series-parallel dual filter-FACTS device comprising tuned arm filter and switched/modulated capacitive compensation scheme. It is controlled by a multi weighted loops using a dynamic error driven-error scaled control scheme for pulse width modulation to ensure effective dynamic voltage stabilization. The proposed dual action MSPFC scheme is shown in Fig. 1.

This device is a low cost modified tuned arm switched/modulated filter and a switched shunt capacitor bank connected to the AC side of the three-arm 6 pulse-diode uncontrolled rectifier with the additional series switched capacitor bank. The operational mode of the MSPFC FACTS can be described as follows based on the controlling PWM switching signals: Switch S_b is controlled by PWM pulses through P_2. Whereas the switching signals are controlled by pulses comes from the PWM unit through P_1. These two complementary switching pulses follow the (NOT LOGIC) command, which is while P_1 is on P_2 is off and vice versa. It means the switch Sa-operation dictates on-off state of the series capacitor bank. While other complementary solid-state switch S_b is on, The FACTS device provides reactive power using a shunt capacitor bank.

2.2. Robust fast dynamic control design

(1) Weighted Modified PID (WMPID) Controller

The classical PID control scheme is one of the widely used simple and efficient control schemes, where the error signal to the PID controller is the sum of four dynamic error signals that were com-

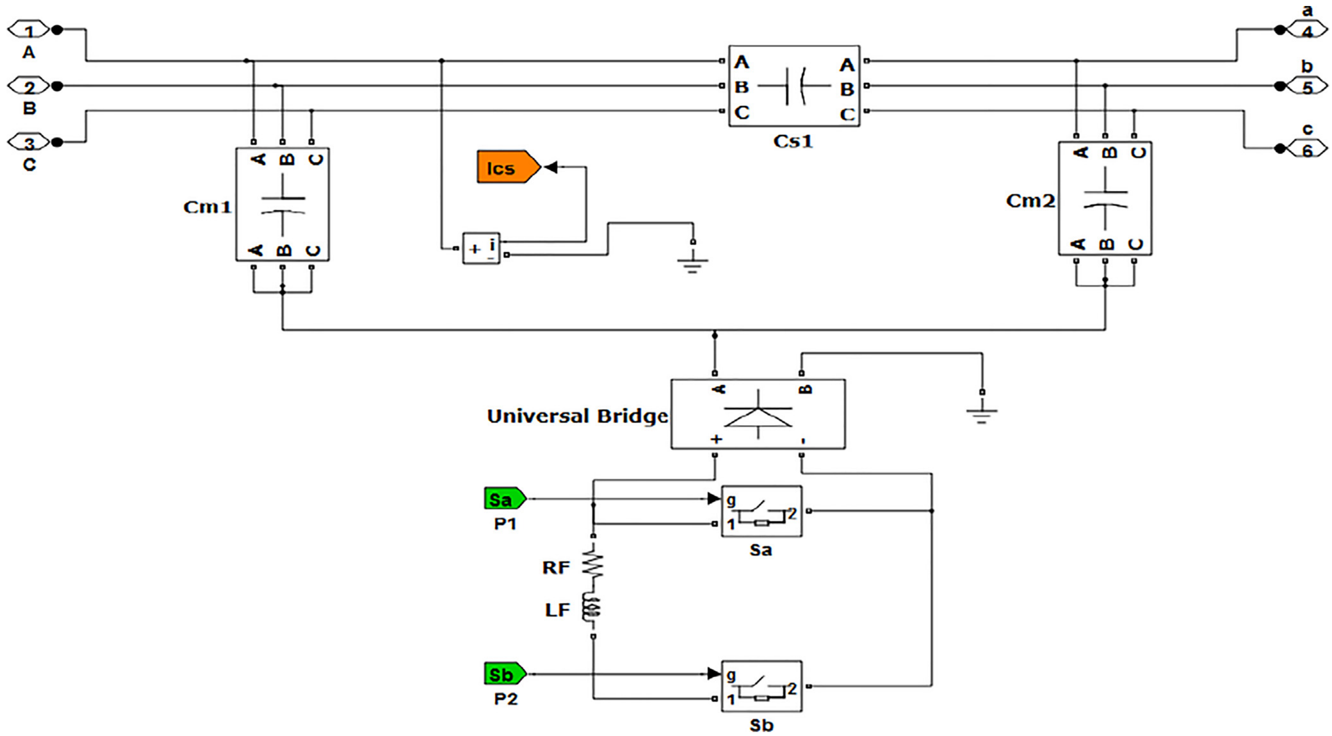

Fig. 1. Hybrid FACTS based Series-Parallel Dual-Action Modulated Switched Power Filter Compensator scheme located at the transmission line-mid-point.

ing from four regulating loops as shown in Fig. 2a. The accumulated error signal to the controller is the sum these four dynamic loop errors as follows:

$$e_t = \gamma_{Vg} e_{Vg} + \gamma_{Ig} e_{Ig} + \gamma_{Pg} e_{Pg} + K_c e_c \tag{1}$$

$$e_{Vg}(pu) = V_{gref}(pu) - \left(\frac{1}{1+T_1 s}\right) V_{RMS}(pu) \tag{2}$$

$$e_{Ig}(pu) = \left(\frac{1}{1+T_2 s}\right)\left(I_{g(pu)}(k) - I_{g(pu)}(k-1)\right) \tag{3}$$

$$e_{pg}(pu) = \left(\frac{1}{1+T_3 s}\right)\left(V_{g(pu)} I_{g(pu)}(k) - V_{g(pu)} I_{g(pu)}(k-1)\right) \tag{4}$$

$$e_{Ics}(pu) = \left(\frac{1}{1+T_4 s}\right)\left(I_{cs(RMS)}(k) - I_{cs(RMS)}(k-1)\right) \tag{5}$$

where γ_{vg}, γ_{Ig}, γ_{Pg} and K_c are the selected optimized loop weightings of each loop error and they are assigned for fast and stable dynamic system operation. The global error (e_t) is handled by the PID controller to generate the modified input signal reference for the PWM signal generator block, which generates two pulses by comparing the tri-wave carrier waveform with the signal modulation signal. Fig. 2a shows the weighted modified WMPID multi regulator weighted error driven control structure.

(2) Modified Incremental Fuzzy Logic controller (MIFLC)

The modified incremental fuzzy logic (MIFLC) using multi loop dynamic error driven controller is used to ensure robust and fast dynamic error damping control as well as efficient energy utilization. The Modified Incremental Fuzzy Logic controller design is shown in Fig. 4. The global error (e_t) and rate of error ($\dot{e}_t$) were utilized as the fuzzy input variables. The scaling gains G_e, G_r and G_u are utilized for descaling of control effectiveness in the global error and rate of error and output gains respectively. The value u is defined as:

$$\boldsymbol{u} = \begin{cases} \boldsymbol{G}_{\boldsymbol{u}\times(\boldsymbol{u}^*)} & \boldsymbol{if}\,|\boldsymbol{e}_t| < \theta(\boldsymbol{fort} = 0, \boldsymbol{G}_{\boldsymbol{inc}} = 0) \\ \boldsymbol{G}_{\boldsymbol{inc}} + \boldsymbol{Inc} & \boldsymbol{if}\,|\boldsymbol{e}_t| > \theta \end{cases} \tag{6}$$

where θ is a boundary selected by tuning and G_{inc} is the incremental gain obtained by adding the increment (*Inc.*). Fig. 3 shows the flowchart for the incremental gain of u.

The basic elements of MIFLC structure, namely as:

- Fuzzification interface: It converts the crisp of input variables into fuzzy values that the inference engine can easily use to activate and apply the base rule. The global error (e_t) and its rate of error ($\dot{e}_t$) were utilized as the fuzzy input variables. Five Gaussian fuzzy sets are chosen for each input variable. The control action is u^* represents the MIFLC output and described by a five Gaussian membership functions. It defined as Gaussian partitions with five segments from -1 to 1. These five segments called linguistic terms such as: Zero (Z) for the center membership function which is centred at zero. The partitions are also symmetric about the Z membership function as shown in Fig. 5. The remaining parts of the partition are Negative Large (NL), Negative Small (NS), Positive Small (PS), Positive Large (PL). Fig. 5(a, b and c) shows membership functions of input/output variables.
- A set of rules, which contain a quantitative assessment of the linguistic description of "experts" on how to achieve good control. The output of the fuzzy rules is calculated based on the minimum of the maximum method. Table 1 has a very useful special feature for the two inputs and one output. Fig. 5d shows surface viewer. It shows the rules viewer of the control action change based on input variables in 3D.

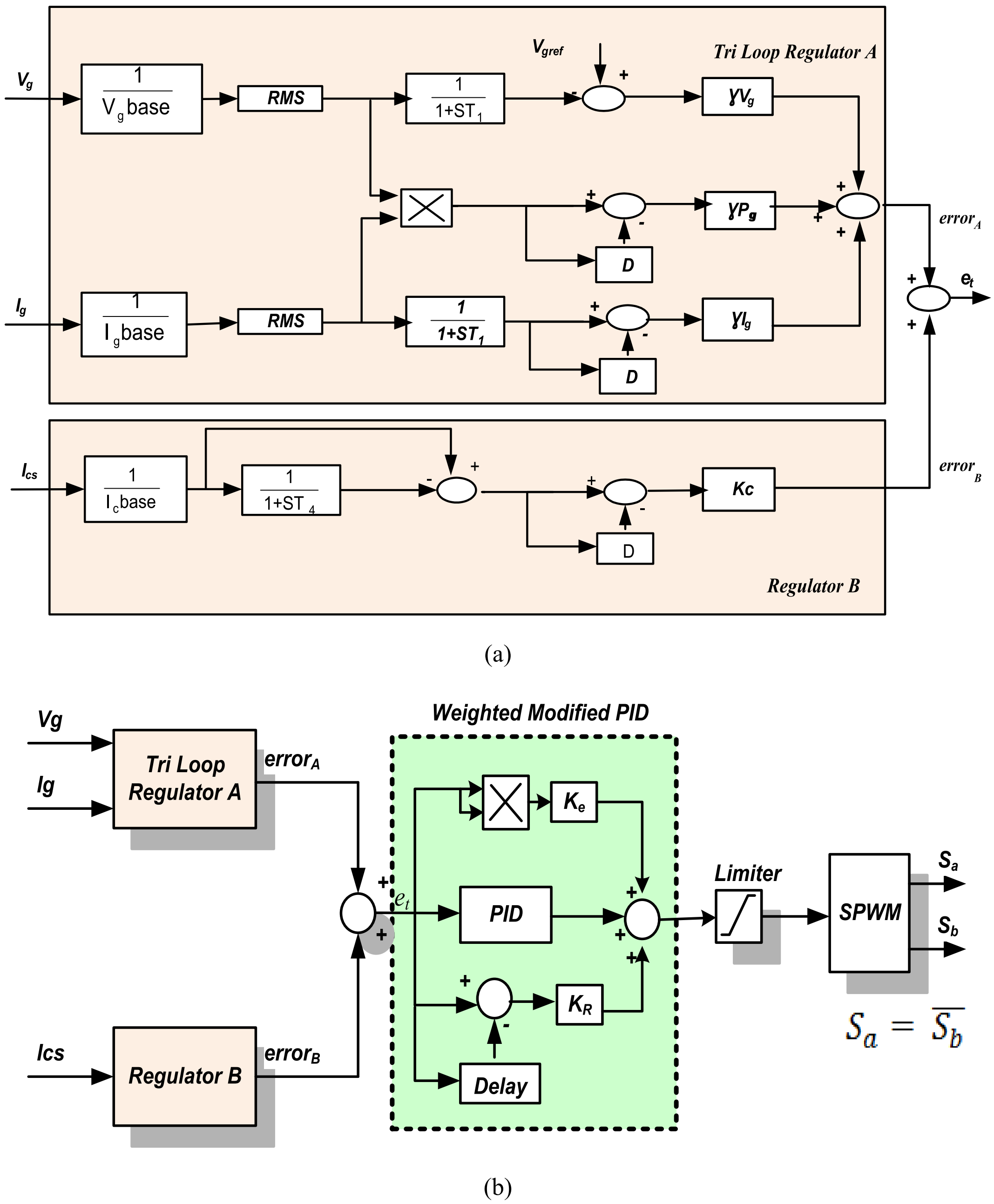

Fig. 2. The weighted modified WMPID multi regulator weighted error driven control structure.

- An inference engine, "mimics" the "expert" knowledge decision based on the quality of control in a process.
- The defuzzification interface translates fuzzy control action to non-fuzzy control action, i.e. numerical values are computed using a digital Center of Area (COA) based on the fuzzy rules shown in Table 1. Fig. 6 shows the defuzzification process based on COA. First, the minimum value of the input variables (e_t, and $\dot{e}_t$) is determined for each rule. This minimum membership is used to rescale the output rule. The maximum of the whole output fuzzy rules represents the polygon map. Then, COA used to compute the fuzzy output, which represents defuzzification stage, as follows:

$$U = \frac{\int y\mu(y)dy}{\int \mu(y)dy} \tag{7}$$

3. Digital simulation results

3.1. Sample study AC system

The unified AC sample SMIB-Single Machine Infinite Bus study system configuration is shown in Fig. 7. This system was modeled and comprised a hybrid composite AC load of linear, converter type nonlinear and induction motor loads that connected to the load bus as was fully modeled using MATLAB/SIMULINK Software Environment. Table 2 constitutes the data of system generation, motor, transmission lines. Also, the values of the weighting factors and PID controller parameters and time constants (T_1-T_4) are reported in Table 2.

The modified switched power filter compensation stage is located at large generator bus. Three cases are implemented to

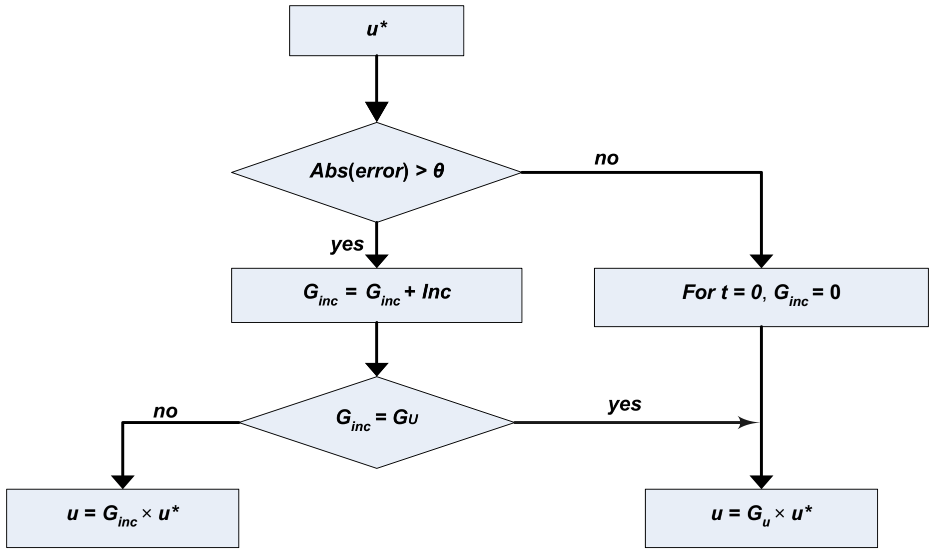

Fig. 3. The flowchart for the incremental gain of *u*.

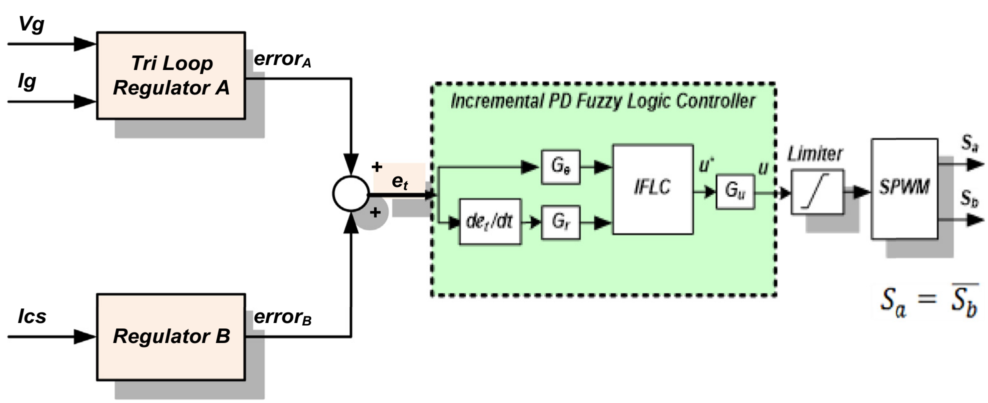

Fig. 4. The Modified Incremental Fuzzy Logic controller design.

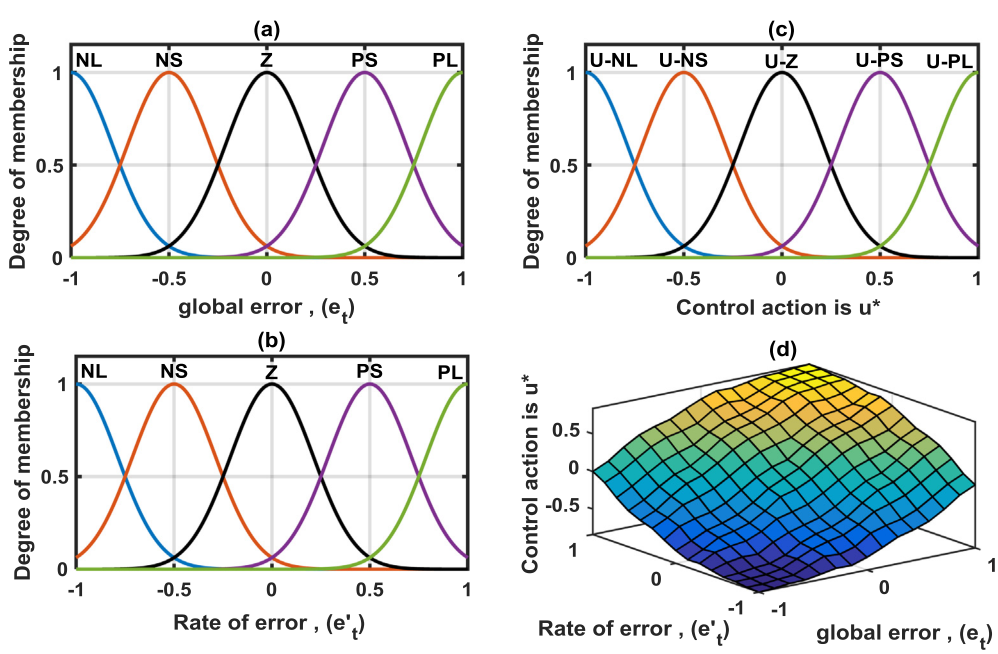

Fig. 5. (a, b) Membership Functions (*MFs*) for input variables of IFLC: (c) Membership Functions (*MFs*) for output variable of IFLC. (d) Rules Surface Viewer of the IFLC.

Table 1
Rule assignment matrix generated for the MIFLC.

		The global error; e_t				
Rate of error; $\dot{e}_t$		**NL**	**NS**	**Z**	**PS**	**PL**
	NL	U-NL	U-NL	U-NL	U-NS	U-Z
	NS	U-NL	U-NL	U-NS	U-Z	U-PS
	Z	U-NL	U-NS	U-Z	U-PS	U-PL
	PS	U-NS	U-Z	U-PS	U-PL	U-PL
	PL	U-Z	U-PS	U-PL	U-PL	U-PL

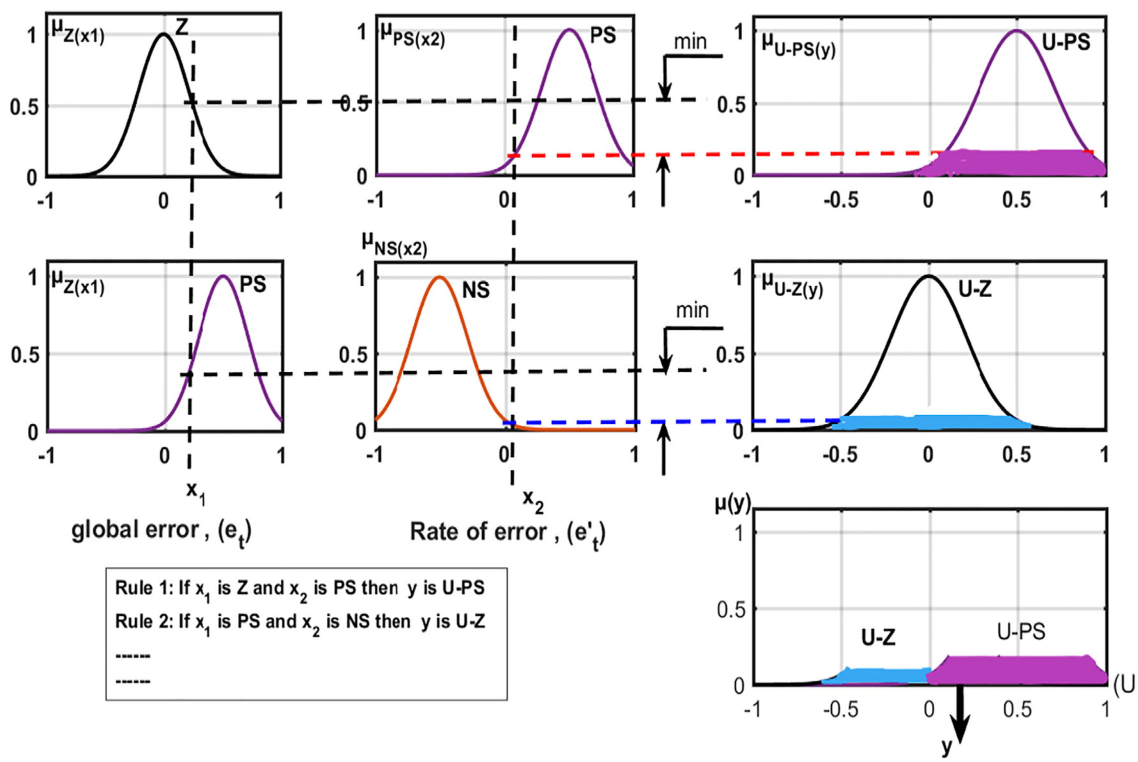

Fig. 6. Center of area (COA) Mamdani defuzzification process.

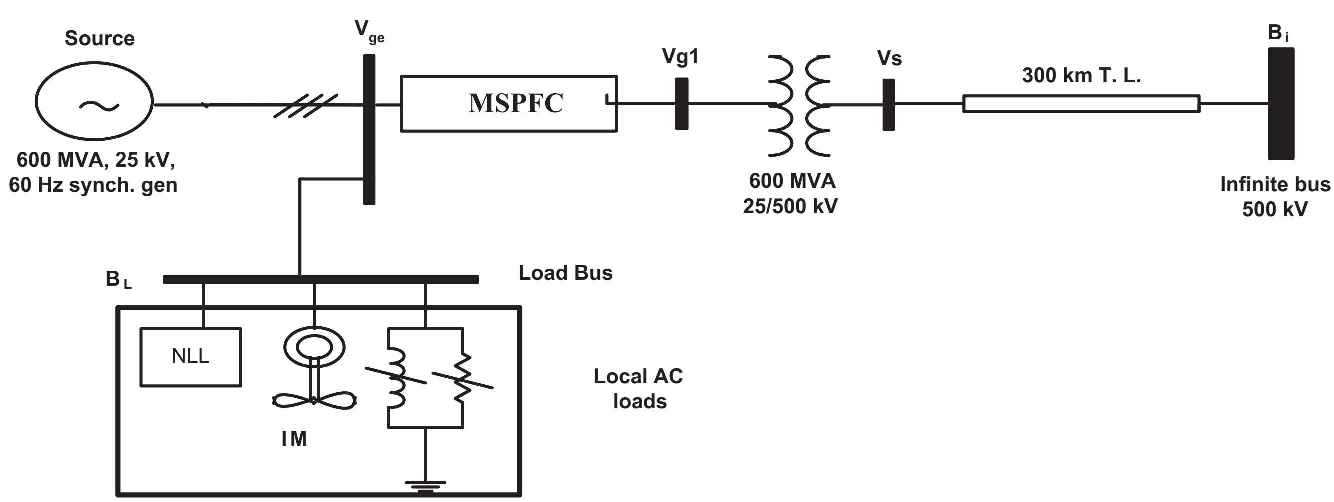

Fig. 7. AC SMIB-Study System with Dual MSPFC-FACTS scheme.

prove the capability of the proposed FACTS scheme for enhancing the system performance under normal, loading and for faulted conditions. For each case, the performance of each controller is assessed in terms of the following captures: Voltage -RMS levels at load bus, current signals through transmission systems, power factor and Active and reactive powers. These measures are considered to observe the voltage profile enhancement and the energy utilization for various operating condition.

Table 2
Test system data and proposed controllers' parameters.

Steam Turbine:	Pout = 600 MW,			**IFLC linguistic variables:**		**Tri-Loop:**
	Speed = 3600 rpm.			*mf: membership function.*		
Synchronous Generator:	*3Ph.*, 2 poles			*NL; Negative Large.*		T_1 = 5 ms
				NS; Negative Small.		T_2 = 10 ms
				Z; Zero.		T_3 = 5 ms
				PS; Positive Small.		T_4 = 20 ms
				PL; Large.		T_5 = 30 ms
						T_6 = 20 ms
						Delay = 5–10 ms
						γ_{Vg} = 1
						γ_{Pg} = 0.25
						γ_{Ig} = 0.5
						γ_{Vg_rep} = 1
						γ_{Pg_rep} = 1
						γ_{Ig_rep} = 0.5
						Kc = 1
						Controller gains:
						Kp = 0–15,
						Ki = 0–1;
						Kd = 0–1, Ke = 0–1
	Vg = 25 KV (L-L),					
	Sg = 600MVA					
	Xd = 1.79 pu	Xd′ = 0.169 pu	Xd″ = 0.135 pu			
	Xq = 1.71 pu	Xq′ = 0.228 pu	Xq″ = 0.2 pu			
	X1 = 0.13 pu					
Transmission line:	500 KV (L-L), 300 km R/km = 0.01273 Ω, L/km = 0.9337mH					
Infinite Bus:	500 kV			**IFLC**		
MSPFC Parameters:	$C_{f1} = C_{f2}$ = 250 µf			**Input variables:**	**Output variable:**	
	C_L = 15 µf, R_f = 1.5 Ω, L_f = 3 mH			Global error (e_t) and change of error ($\acute{e}_t$).	The output signal (*U*)	
SPWM:	$P_2 = P_3 = \bar{P}_1$, Fs/w = 1750 Hz					
Motor	Ratings: 30 HP, Voltage = 25 kV, 60 Hz Rr = Rs = 0.01909p.u., Lr = Ls = 0.0397, Lm = 1.354 Inertia J = 0.09526, Friction f = 0.05479, No of poles = 2					

3.2. AC system response under normal operating conditions

For normal operating condition, Fig. 8 illustrates the dynamic system responses of active power, power factor, reactive power, (*RMS)* voltage respectively at load and generation buses in presence of the new FACTS based MSPFC-FACTS controlled by MIFLC and MPID controllers. It is cleared that the use of FACTs devices enhances the voltage levels by around 10% compared to non-compensated case. For the second measure, the level current is also reduced from 0.7 pu to around 0.6 in the case of WMPID and MIFIC that consequently reduces the transmission losses. It improves the power factor at load and generation buses by around 20% and 10%, respectively. Added to that, the reactive power at generation buses is released by around 50% in the presence of the proposed FACTs scheme. The previous measures lead to efficient energy utilization. The AC bus power exchanges between infinite bus and machine system can be either positive or negative based on operating and fault/load conditions. The power flow from *Vg* bus to infinite slack/swing bus is usually governed by power angle difference and the reactive Power exchanges by AC Bus-Voltage RMS magnitudes. The infinite bus can receive or send the active and reactive power to other system via the feeder. So operating conditions can cause reversal in power flow from infinite bus to the generator bus.

The global error (e_t) for both controllers under normal operations is shown in Fig. 9. The performance is compared in terms of criteria such as Integrated Absolute Error (IAE) and some statistical analysis for the global error (e_t) for the both MPID and MIFLC controllers under normal operations as in Table 3. The IAE for MIFLC is 1.073 and 2.129 for MIPD respectively. The simulation results showed that the robustness and the proposed MIFLC is better.

3.3. System dynamic response under hybrid load excursions/variations

The dynamic system response is examined under hybrid load changes and sudden changes in the AC system as follows: Linear load is rejected at time = 0.1–0.15 sec, Non-Linear load is rejected at time = 0.2–0.25 sec, Motor load Torque; Tm at = 50% at time = 0.3–0.35 s and Motor load Torque; Tm at = 150% at time = 0.4–0.45 s. Figs. 10 and 11 illustrate simulation responses of Power, Power Factor, Reactive Power, RMS-Voltage at Load bus in presence of MSPFC-FACTS controlled by MIFLC and Weighted-Modified PID controllers and without MSPFC-FACTS. It is cleared that the use of FACTs devices enhances the voltage levels by around 10% compared to non-compensated case.

For the second measure, the level current is also reduced from 0.7 pu to around 0.6 in the case of WMPID and MIFIC that consequently reduces the transmission losses. It improves the power factor at load and generation buses by around 20% and 10%, respectively. Added to that, the reactive power at generation buses is released by around 50% in the presence of the proposed FACTs scheme. The proposed controllers' behavior enables perfectly following the load nature variations and helps the generator to smoothly submit the required active power by the demand. Also, the use of FACTs device with proposed controllers preserve the active and reactive powers received at infinite bus with less affected by the hybrid variation in the loading nature at the load bus. The previous measures lead to efficient energy utilization during hybrid load variation.

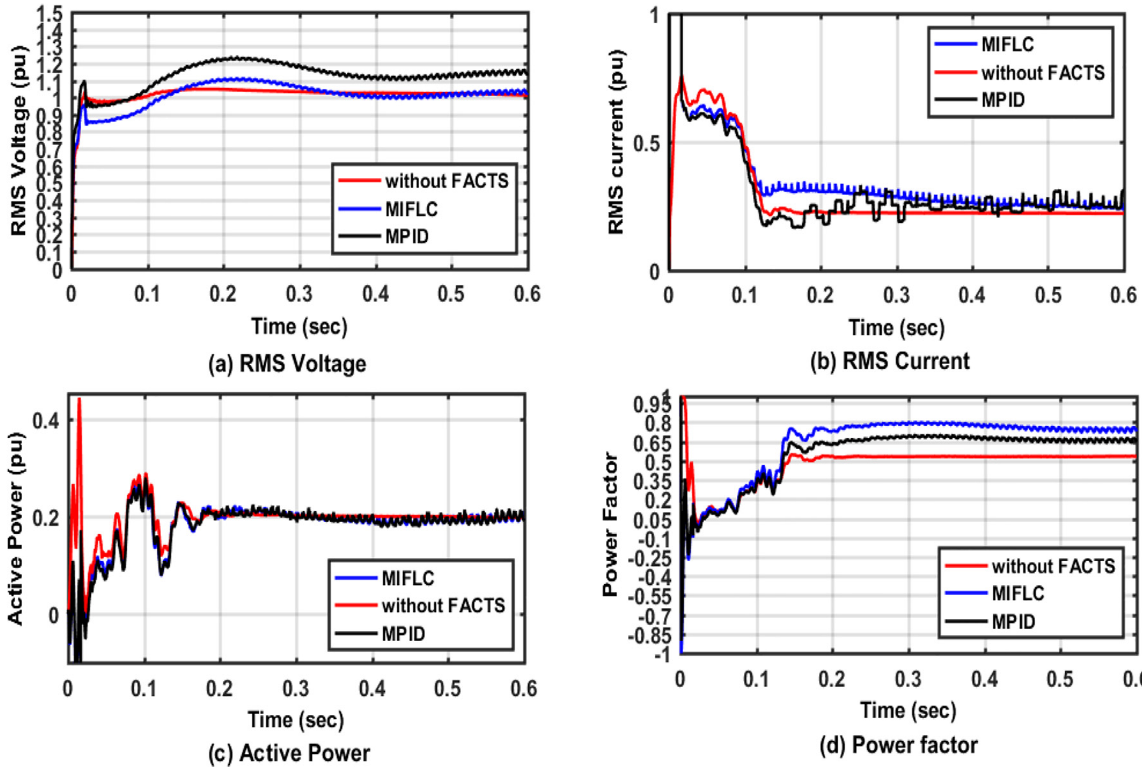

Fig. 8. Dynamic response at load bus with the proposed FACTs device controlled by MIFLC and WMPID controllers.

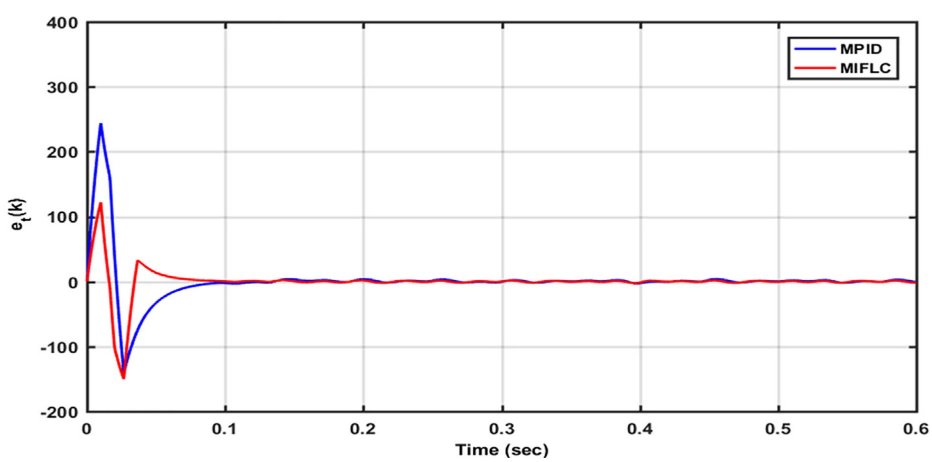

Fig. 9. The global error (e_t) for both controllers under normal operations.

Table 3
Statistical analysis for the both MPID and MIFLC controllers under normal operations.

	Time	MPID	MIFLC
Min	0	−140.338	−150.1940
Max	0.6	243.774	121.8045
Mean	0.2992	1.0943	0.0226
Medium	0.2989	0.3038	0.2554
Mode	0	−124.7056	−105.4239
STD	0.1731	35.05	21.2252
Range	0.6	384.11	272

The statistical analysis for the global error (e_t) in case of load variations is shown in Table 4. Fig. 12 shows the global error (e_t) for both controllers under hybrid load variation condition. The IAE for MIFLC and MIPD are 1.761 and 3.371, respectively. The simulation results showed that the robustness of the proposed MIFLC is better that MIPD.

3.4. Dynamic system response under Severe-Fault conditions

The AC system is examined under three phase short circuit fault for time = 0.2–0.3 sec at Vs bus. Figs. 13–14 illustrate dynamic system responses of Power, Power Factor, Reactive Power, RMS-Voltage at Load bus in presence of MSPFC-FACTS controlled by MIFLC and MPID controllers and without of MSPFC-FACTS. Without the presence of FACTs devices, the voltage during the fault period is declined to approximately 50% of the pre-fault voltage levels. The use of FACTs devices enhances the voltage levels during the fault period, and it was preserved at around 1.1 pu during the faulty condition.

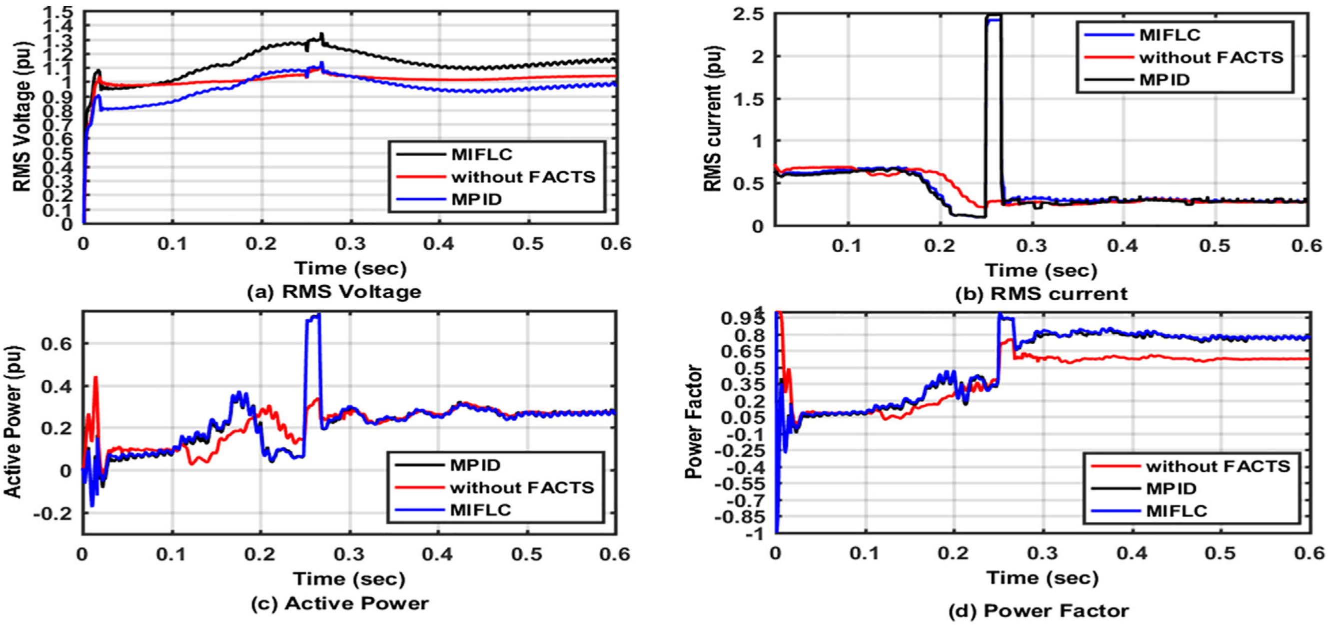

Fig. 10. Dynamic system response at load Bus for hybrid load variations.

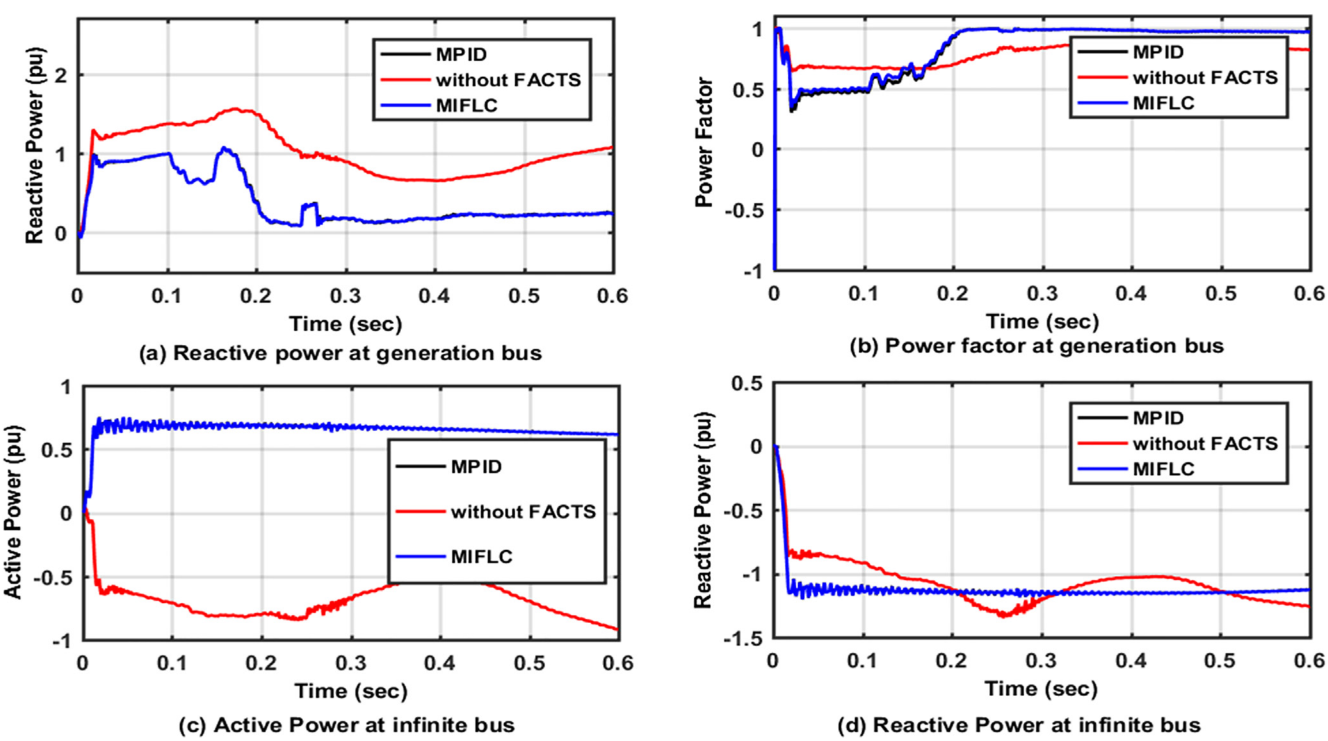

Fig. 11. Dynamic system response at generation and infinite buses under hybrid load variation condition.

Table 4
Statistical analysis for the both MPID and MIFLC controllers under hybrid load variation condition.

	Time	MPID	MIFLC
min	0	−140.3433	−150.1965
max	0.6	243.7746	121.8045
mean	0.2992	1.0737	0.0270
Medium	0.2989	0.2902	0.3222
Mode	0	−2.0235	0.1422
STD	0.1731	35.3261	21.3908
Range	0.6	384.1179	272

For the RMS current is also reduced to the healthy condition level that consequently reduces the impacts of the faulty condition. The use of FACTs device with the proposed controllers improves the power factor at load and generation buses during the fault period by around 20% and 50%, respectively. Added to that, the reactive power at generation buses is released by around 50% in the presence of the proposed FACTs scheme. The active power transmitted during faulty period is still at its pre-fault level that reflects ability of the proposed FACTS device to assure the continuity of active power delivered to the load bus during the faulty period. The previous measures lead to efficient energy utilization even at faulty condition.

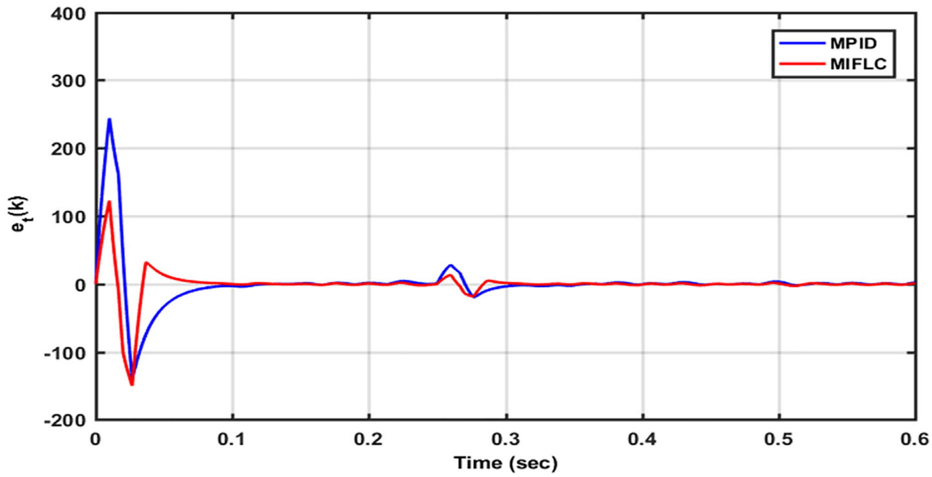

Fig. 12. The global error (e_t) for both controllers under hybrid load variation condition.

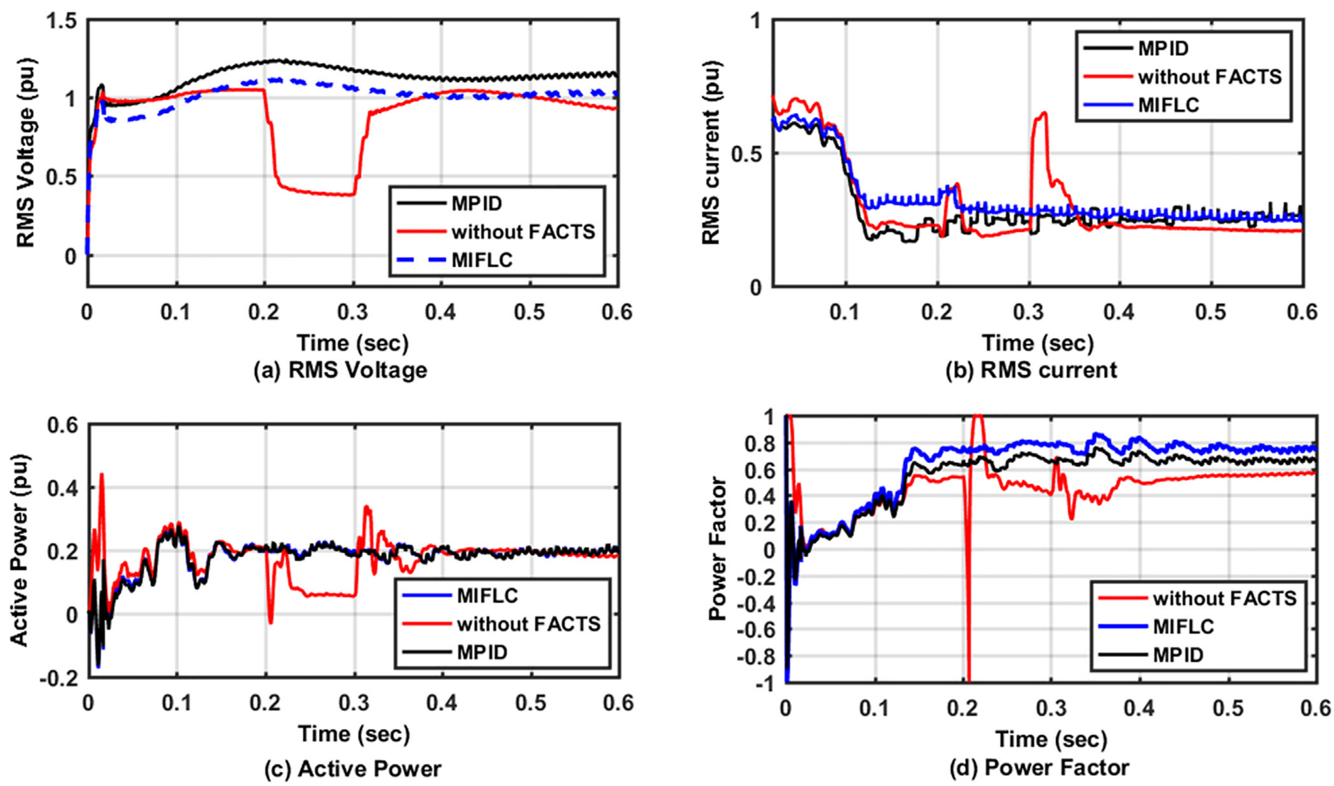

Fig. 13. Dynamic system response at load bus for three phase short-circuit fault condition at Vs bus.

Fig. 15 shows the global error (e_t) for both controllers under three phase short circuit fault condition at Vs bus. The statistical analysis for the global error (e_t) in case of three phase short circuit fault condition at Vs bus is presented in Table 5. The IAE for MIFLC is 1.559 and 2.89 for MIPD respectively. The simulation results show that the high robustness of the proposed MIFLC is better.

3.5. Future extensions

The following items present the possible extensions and future work of the proposed controller:

- Other FACTS-smart grid applications such as:
- Energy storage/fuel cell,
- battery renewable energy systems hybrid AC-DC interface topologies
- VSC-converter interfacing.
- electric vehicle V2H/V2G battery charging
- industrial DC/AC motor drives used in Process Industries,
- Water Pumping
- Ventilation Applications.
- The validated Hybrid FACTS based dual Switched series - Parallel Filter and compensation device using new meta heuristic search and Optimization methods is now extended to online

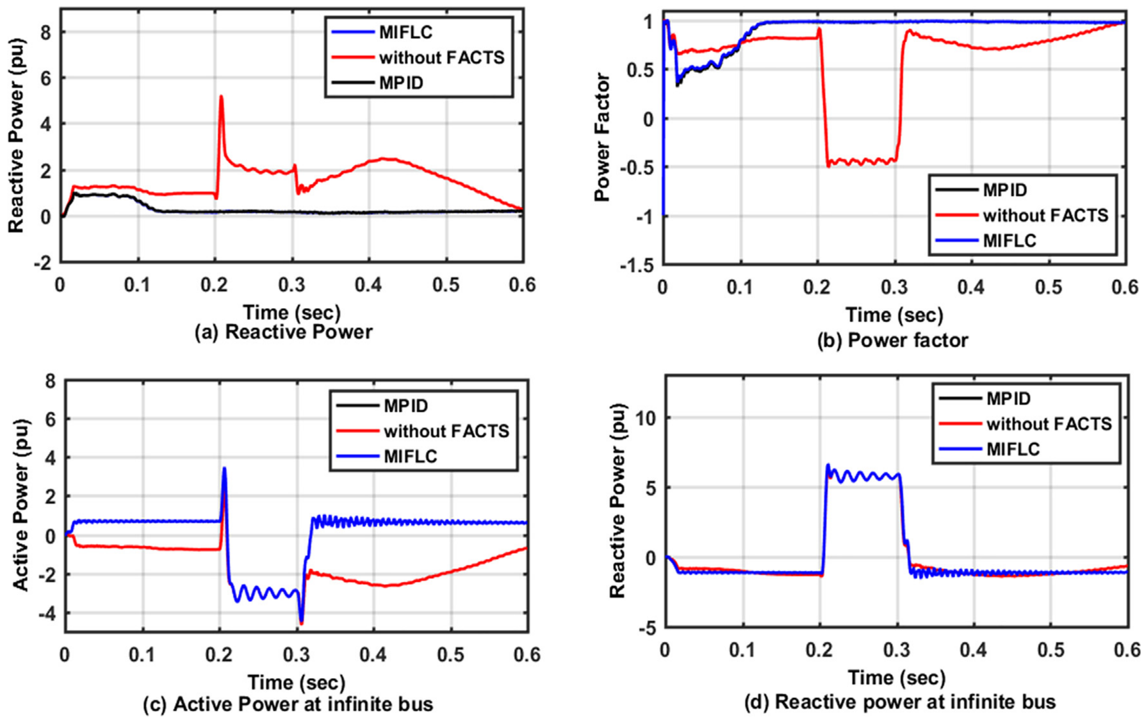

Fig. 14. Dynamic system response at generation and infinite buses under three phase short circuit fault condition at Vs bus.

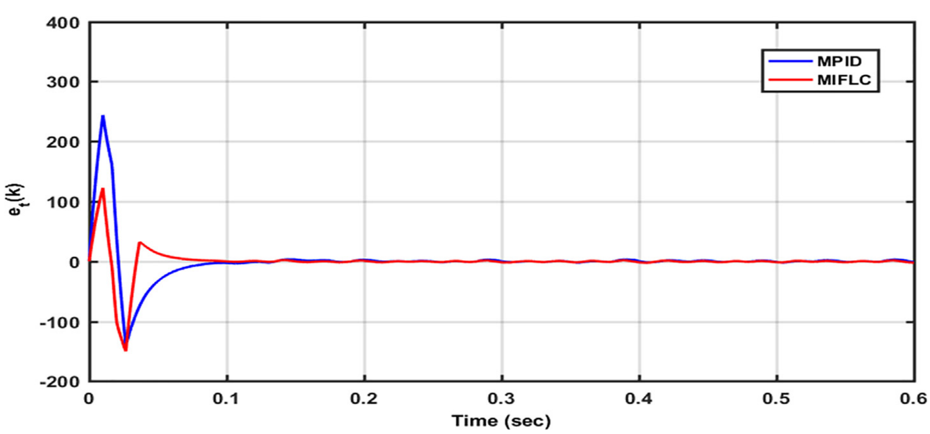

Fig. 15. The global error (e_t) for both controllers under three phase short circuit fault condition at Vs bus.

Table 5
Statistical analysis for the both MPID and MIFLC controllers under three phase short circuit fault condition at Vs bus.

	Time	MPID	MIFLC
min	0	−140.3	−150.194
max	0.6	243.8	121.804
mean	0.2992	1.089	0.0254
Medium	0.2989	0.2453	0.194
Mode	0	2.2257	1.072
STD	0.1731	35.0557	21.225
Range	0.6	384.11	272

adaptive gains and topologies using PSO, Harmony, Ant, Weed Invasion, Bacteria foraging, moth-flame and sunflower optimization methods.

- The same FACTS device is now extended to Renewable Energy wind and tidal/ wave schemes to ensure dynamic voltage stabilization, enhanced power quality and improved energy utilization at the interface bus of the host smart grid.

4. Conclusions

In this paper, the proposed dual action FACTS based series-parallel switched series-parallel filter/compensator device has been developed and validated for sample study AC power system with two control strategies. The novel dual acting modulated FACTS filter/Capacitive compensation device is a hybrid series - parallel filter that is dynamically modulates the equivalent Thevenin's impedance at the interface bus to endure a dynamic compensation level and controlled reactive compensation as required by the host electric grid. The unified sample study system was digitally simulated and validated for AC load changes, sudden excursions, short circuit faults as well as normal operation to assess efficient energy utilization, power factor improvement, power quality enhancement, voltage stabilization and inrush current conditions as well as voltage transients during the sub-transient and transient faulty periods. Both modified WMPID with fixed gain and modified incremental fuzzy logic MIFLC- Controller were assessed and compared for robustness in terms of fast dynamic response, improved voltage regulation transients, enhanced power quality and improved power factor. The MIFLC controller design was found to perform better in terms of fast dynamic response and response times with slightly reduced inrush currents and reduced voltage transients with enhanced voltage regulation and bus voltage-stabilization. The performance of the proposed controller has been assessed using statistical assessment of the controller performance is carried out for different operating conditions

References

[1] Bari Ataul et al. Challenges in the smart grid applications: an overview. Int J Distrib Sens Netw 2014;10(2):974682.

[2] Mouwafi MT et al. Optimal placement of phasor measurement units with minimum availability of measuring channels in smart power systems. Electr Power Syst Res 2016;141:421–31.

[3] Li Fangxing et al. Smart transmission grid: vision and framework. IEEE Trans Smart Grid 2010;1(2):168–77.

[4] Sharaf AM, Gandoman FH, Rahimi A. A flexible alternating current transmission system-green plug scheme for smart grid applications. Turk J Electrom Energ 2016;1(1):13–20.

[5] Deepak Divan, Johal Harjeet. Distributed FACTS-A new concept for realizing grid power flow control. InL 2005 IEEE 36th power electronics specialists conference. IEEE; 2005.

[6] Chandra Ambrish et al. An improved control algorithm of shunt active filter for voltage regulation, harmonic elimination, power-factor correction, and balancing of nonlinear loads. IEEE Trans Power Electron 2000;15(3):495–507.

[7] Sharaf Adel M, Gandoman Foad H. A robust FACTS PV-smart grid interface scheme for efficient energy utilisation. Int J Power Energy Convers 2015;6(4):344–58.

[8] Shafik MB, Chen Hongkun, Rashed Ghamgeen I, El-Sehiemy RA, Elkadeem MR, Wang Shaorong. Adequate topology for efficient energy resources utilization of active distribution networks equipped with soft open points. IEEE Access 2019;7:99003–16.

[9] Shafik MB, Chen Hongkun, Rashed Ghamgeen I, El-Sehiemy Ragab A. Adaptive multi objective parallel seeker optimization algorithm for incorporating TCSC devices into optimal power flow framework. IEEE Access 2019;7:36934–47.

[10] Shafik MB, Rashed GI, El-Sehiemy Ragab A, Chen Hongkun. Optimal sizing and sitting of TCSC devices for multi-objective operation of power systems using adaptive seeker optimization algorithm. In: 2018 IEEE Region Ten Symposium (Tensymp); 2018. p. 231–6. IEEE.

[11] Maharjan Sabita et al. Demand response management in the smart grid in a large population regime. IEEE Trans Smart Grid 2015;7(1):189–99.

[12] Adly Ahmed R et al. Critical aspects on wavelet transforms based fault identification procedures in HV transmission line. IET Gener Transm Distrib 2016;10(2):508–17.

[13] Adly Ahmed R, El Sehiemy Ragab A, Abdelaziz Almoataz Y. A novel single end measuring system based fast identification scheme for transmission line faults. Measurement 2017;103:263–74.

[14] Zaki Mohamed I, El-Sehiemy Ragab A, Amer Ghada M, Abo Fathy M, Enin El. An investigated reactive power measurements-based fault-identification scheme for teed transmission lines. Measurement 2019;136:185–200.

[15] Zaki Mohamed I, El Sehiemy Ragab A, Amer Ghada M, Abo Fathy M, Enin El. Sensitive/stable complementary fault identification scheme for overhead transmission lines. IET Gener Transm Distrib 2019;13(15):3252–63.

[16] Amama Sid-Ali, Ahmed Hafiz, El-Sehiemy Ragab A. Firefly algorithm optimized robust protection scheme for DC microgrid. Electr Power Compon Syst 2017;45(10):1141–51.

[17] El-Ela Adel A, Abou Ragab A, Eman Salah Ali El-Sehiemy, Kinawy Abdel-Mohsen. Minimization of voltage fluctuation resulted from renewable energy sources uncertainty in distribution systems. IET Gener Transm Distrib 2019;13(12):2339–51.

[18] Chen Changsong et al. Smart energy management system for optimal microgrid economic operation. IET Renew Power Gener 2011;5(3):258–67.

[19] Asmaa Elsakaan, El Sehiemy Ragab, Kaddah Sahar, Elsaid Mohammed. Optimal economic/emission power scheduling of renewable energy resources in microgrids with uncertainty. IET Gener, Transmiss Distrib 2019. doi. 10.1049/iet-gtd.2019.0739.

[20] Shanthi P, Govindarajan U, Parvathy Shankar D. Instantaneous power-based current control scheme for VAR compensation in hybrid AC/DC networks for smart grid applications. IET Power Electron 2014;7(5):1216–26.

[21] Močnik J, Žemva A. Controlling voltage profile in smart grids with remotely controlled switches. IET Gener Transm Distrib 2014;8(8):1499–508.

[22] Attia Abdel-Fattah. Intelligent controller for tracking a 14-inch Celestron telescope. Acta Polytech 2018;58(5):271–8.

[23] Gaing ZL. A particle swarm optimization approach for optimum design of PID Controller in AYR System. IEEE T Energy Conver 2004;9(2):384–91.

[24] Attia Abdel-Fattah, Soliman H, Sabry M. Genetic algorithm-based control system design of a self-excited induction generator. Acta Polytech 2006;46(2):11–22.

[25] Attia Abdel-Fattah. Hierarchical fuzzy controllers for an astronomical telescope tracking. Appl Soft Comput. 2009;9(1):135–41.

[26] Sharaf AM, Aljankawey A, Altas IH. A novel voltage stabilization control Scheme for stand-alone wind energy conversion systems. Proc Conf Clean Elect Power, ICCEP 2007 2007:514–9.

[27] Sharaf AM, Wang G. Wind energy system voltage and energy enhancement using low cost dynamic capacitor compensation scheme. In: Proceedings of the IEEE international conference on electrical, electronic and computer engineering; 5-7 Sept. 2004. p. 804–807.

[28] Elhosseini Mostafa A, El Sehiemy Ragab A, Salah Amgad H, Abido MA. Modeling and control of an interconnected combined cycle gas turbine using fuzzy and ANFIS controllers. Electr Eng 2018;100(2):763–85.

[29] Soliman Mahmoud A, Hasanien Hany M, Azazi Haitham Z, El-Kholy Elwy E, Mahmoud Sabry A. An adaptive fuzzy logic control strategy for performance enhancement of a grid-connected PMSG-based wind turbine. IEEE Trans Ind Inf June 2019;15(6):3163–73.

[30] Soliman Mahmoud A, Hasanien Hany M, Azazi Haitham Z, El-Kholy Elwy E, Mahmoud Sabry A. Hybrid ANFIS-GA-based control scheme for performance enhancement of a grid-connected wind generator. IET Renew Power Gener 2018;12(7):832–43.

[31] Muyeen SM, Hasanien Hany M. Operation and control of HVDC stations using continuous mixed p-norm based adaptive fuzzy technique. IET Gener, Transmiss Distrib 2017;11(9): 2275–82.

[32] Hasanien Hany M, Matar Mahmoud. A fuzzy logic controller for autonomous operation of a voltage source converter-based distributed generation system. IEEE Trans Smart Grid 2014;6(1):158–65.

[33] Gandoman Foad H, Ahmadi Abdollah, Sharaf Adel M, Siano Pierluigi, Pou Josep, Hredzak Branislav, et al. Review of FACTS technologies and applications for power quality in smart grids with renewable energy systems. Renew Sustain Energy Rev 2018;82:502–14.

[34] Sharaf AM, Abo-Al-Ez KM. A FACTS based dynamic capacitor scheme for voltage compensation and power quality enhancement. In: 2006 IEEE international symposium on industrial electronics 2006; 2: 1200–1205.

[35] Youssef Erhab, Sharaf Adel, Amin Amr, El Samhey Adel. Wind Energy FACTS Applications and Stabilization Schemes. In Advances in Renewable Energies and Power Technologies. Elsevier; 2018. p. 431–60.

[36] Sharaf AM, Chhetri R. A novel dynamic capacitor compensator/green plug scheme for 3-phase 4-wire utilization loads. In: Canadian conference on electrical and computer engineering, 2006, CCECE '06; 2006. p. 454–459.

[37] Sharaf AM, El-Sadek MZ, Abd-Elbar FN, Hemeida AM. A global dynamic error driven control scheme for static VAR compensators. Electr Power Syst Res 1999;51(2):131–41. doi: https://doi.org/10.1016/S0378-7796(98)00147-3.

[38] Attia Abdel-Fattah, Sharaf Adel M. A Novel multistage fuzzy controller for FACTS stabilization scheme for SMIB AC System. J Eng Sci 2015;43(1):45–56.

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