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POWER QUALITY ENHANCEMENT USING SHUNT ACTIVE POWER FILTER WITH FUZZY LOGIC CONTROL OF ROBUST LQG SERVO CONTROL STRATEGY

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ABSTRACT- In this paper, a shunt active power filter based on fuzzy logic controller is designed. This paper proposes a Linear Quadratic Gaussian (LQG) Servo controller for the current control of Shunt Active Power Filter (SAPF) operating under balanced and unbalanced supply voltages. A fuzzy logic controlled shunt Active Power Filter (SAPF) Using Hysteresis Band Current (HBC) is applied to regulate the DC capacitor voltage of (SAPF) in order to improve the active filter dynamic, to ensure sinusoidal source currents and to produce a high power quality.. This LQG controller is comprised of a LQ regulator and a Kalman filter (KF) that minimizes the error between the output currents and their variations. Here we are using the fuzzy controller compared to other controllers i.e. The fuzzy controller is the most suitable for the human decision-making mechanism, providing the operation of an electronic system with decisions of experts. A feedback compensator is used in LQG Servo controller that benefits a SAPF system by increasing tracking error reduction, gain stability, reducing amplitude distortion and sensitivity to external disturbances. A Kalman filter based new reference current generation scheme is developed. It is demonstrated that the fuzzy logic controller improves the performance of the active power filter. By using the simulation results we can analyze the proposed control strategy exhibits superior performance in terms of robustness improvement and current harmonics mitigation under steady-state and dynamic load conditions.

I. INTRODUCTION

The non-linear loads such as power electronic equipments produce harmonics. The harmonic and reactive power cause poor power factor and distort the supply voltage at the common coupling point or customer service point. Electrical power quality [1], [2] has been a growing concern because of the proliferation of the nonlinear loads, which causes significant increase of line losses, instability and voltage distortion. With injection of harmonic current into the system, these nonlinear loads additionally cause low power factor. The resulting unbalanced current adversely affects every component in the power system and equipment. This results in poor power factor, increased losses, excessive neutral currents and reduction in overall efficiency. Although load compensation using passive filters is simple to design and operate, it has drawbacks such as resonance, detuning and overloading. Moreover, passive filter is not suitable for fast changing loads. The aforesaid issues can be effectively mitigated by employing a SAPF.

This paper present performance improvement of the shunt active power filter that consists of three principal parts, namely, the voltage source inverter, DC energy storage device (Cf) and coupling inductance (Lf). The inverter having six IGBTs switches is used to charge and to discharge the capacitor voltage source in order to provide the required compensation current, the capacitor voltage source is used to store energy and the inductance is used to smoothen the ripple of the harmonic current injected by shunt active power filter. The input supply voltage source provides the required active power and the capacitor voltage source of shunt active power filter provides the reactive power for the load. The load is a three-phase full-bridge diode rectifier supplying a RL load, shown as (Fig. 1).

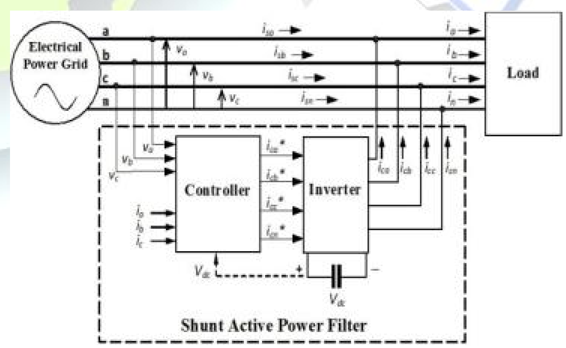

Fig. 1: Three-phase Shunt Active Power Filter system

A linear quadratic control combined with an integral control has been employed to control a three phase three wire SAPF to achieve unity power factor at PCC of a heavily distorted and unbalanced load currents [6]. This control uses the full state vector

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available for feedback, but this is unrealistic as there is always a measurement noise.

Various control schemes have been applied in SAPF [4], [5] under both balanced and unbalanced loading conditions. However, these control strategies have not considered some important aspects of power system perturbations such as supply unbalance, variations in the SAPF as well as load parameters and grid perturbations such as measurement noise and voltage distortion. Further, due to parametric uncertainties present in the load, the problem of compensating the SAPF becomes more complicated which adversely effects towards its satisfactory operation. A linear quadratic control combined with an integral control has been employed to control a three phase three wire SAPF to achieve unity power factor at PCC of a heavily distorted and unbalanced load currents.

An optimal control theory supported LQR and KF was proposed considering measurement noise, load currents and grid voltage transients. However PCC voltage has not been considered as a disturbance in the SAPF model. LQR law is based on the availability of the complete state vector, which may not be completely measurable in most of the real-world situations. To overcome this, a LQG servo controller was proposed for voltage source converter (VSC) connected to the grid [8], where KF was employed to estimate the state vector. In this case, power system perturbations have not been taken into consideration and also the presence of a time delay at the reference tracking point gives rise to a slow response of the overall system. Thus, tracking error is not reduced effectively and stability of the system is minimally improved.

However, a fast response without any tracking error delay is indispensable for a SAPF system so that efficient current harmonics compensation can be achieved under aforementioned perturbations.

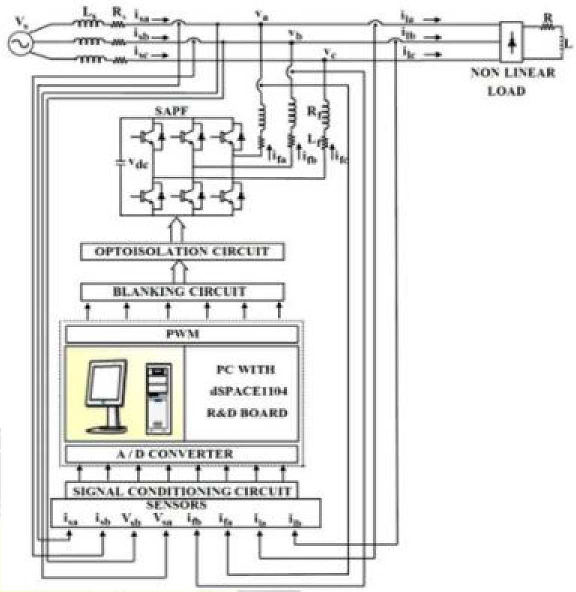

Fig.2: Block diagram of the control and power circuit of SAPF.

It is not possible to supply quality power to the special equipment e.g. programmable logic controller (PLC), distributed control system (DCS), converters in AC drives through conventional control schemes [6]-[8], [11] employed in SAPF. In view of aforementioned issues, we focus on the development of robust LQG servo controller with a faster reference estimation scheme in SAPF, which permits all perturbations such as PCC voltage distortion, measurement noise, parametric variations of load, capacitor voltage and filter impedance, tracking error variations and supply voltage unbalance so that compensation capability of the overall SAPF system can be enhanced. [7] proposed a system in which the complex parallelism technique is used to involve the processing of Substitution Byte, Shift Row, Mix Column and Add Round Key. Using S- Box complex parallelism, the original text is converted into cipher text. From that, we have achieved a 96% energy efficiency in Complex Parallelism Encryption technique and recovering the delay 232 ns. The complex parallelism that merge with parallel mix column and the one task one processor techniques are used. In future, Complex Parallelism single loop technique is used for recovering the original message.

II. DEVELOPMENT OF CONTROL SYSTEM

We present the control algorithm in the development of SAPF in two distinct steps namely reference generation and current controller

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implementation, which are described subsequently as below.

A. Proposed Reference Current Generation Scheme.

When load parameter varies, average voltage across the dc link capacitor deviates from its reference value and the real power supplied by the source is not enough to supply the load demand. The SAPF can't immediately respond to the load change since it takes a longer interval to calculate a new reference current. This drawback is overcome by the proposed reference scheme with a fast and adaptive estimation of peak value of source reference current, which has the capability of delivering real power equivalent to conduction and switching losses occurred during capacitor voltage deviation. This reference estimation approach has merit in avoidance of voltage sensors, tuning problems and synchronization circuits needed for hardware, hence it becomes cost effective.

The proposed scheme is based on source reference generation principle and the reference compensating currents * ifabc for three phases a, b, and c are generated by subtracting the source references * isabc from the load currents ilabc as shown in Fig.(a).

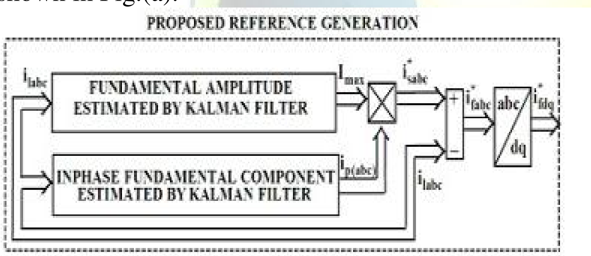

Fig.3: Proposed Control Structure i.e. proposed Reference Generation Scheme,

Source reference current generation is implemented by the modulation of the estimated peak value of source current (I) max with the estimated in phase fundamental components (i) p(abc) of load currents in per unit value, equations of which are provided below.

$$i^*_{sabc} = I_{max} * i_{P(abc)} \quad (1)$$

$$i^*_{fabc} = i_{abc} - i^*_{sabc} \quad (2)$$

For an accurate estimation of reference current, the unit template ip(abc) must be undistorted and this condition is met by Kalman filtering estimation algorithm.

1) Formulation of KF algorithm for reference current generation

A linear signal zk of single sinusoid is represented by

$$z_k = a_1 \sin(k\omega_1 T_s + \emptyset_1) k = 1, \dots, N \quad (3a)$$

$$\omega_1 = 2\pi f_1 \quad (3b)$$

In eq (3), Ts denotes the sampling time, parameters a1 and f1 are the fundamental amplitude and frequency respectively with initial phase 1 . The signal zk 1 can be expressed as

$$z_{k+1} = X_{1k+1} = X_{1k}\cos(k\omega_1 T_s) + X_{2k}\sin(k\omega_1 T_s) \quad (4)$$

$$X_{2k+1} = -X_{1k}\sin(k\omega_1 T_s) + X_{2k}\cos(k\omega_1 T_s) \quad (5)$$

where x2k is known as the in quadrature component and is orthogonal to x1k and they are represented by

$$X_{1k} = a_1 \sin(k\omega_1 T_s + \emptyset_1) \quad (6a)$$

$$X_{2k} = a_1 \sin(k\omega_1 T_s + \emptyset_1) \quad (6b)$$

To model amplitude or phase variations of the signal, a perturbation vector 1 2T k in the system states is considered with the state space representation as

$$X_{k+1} = \emptyset_k x_k + w_k \quad (7)$$

$$y_k = H_k x_k + v_k \quad (8)$$

where wk and vk are the process and measurement noises respectively and the state transition matrix k and the observed value Hk are given below.

$$\emptyset_k = \begin{bmatrix} \cos(\omega_1 T_s) & \sin(\omega_1 T_s) \\ -\sin(\omega_1 T_s) & \cos(\omega_1 T_s) \end{bmatrix} \quad (9)$$

$$H_k = [1 \quad 0] \quad (10)$$

b. Proposed LQG Servo Current Controller

In the proposed LQG Servo controller, we consider a trade off but regulation/tracking performance and the control effort considering both process disturbances and measurement noise. We present next the design of our proposed LQG Servo controller.

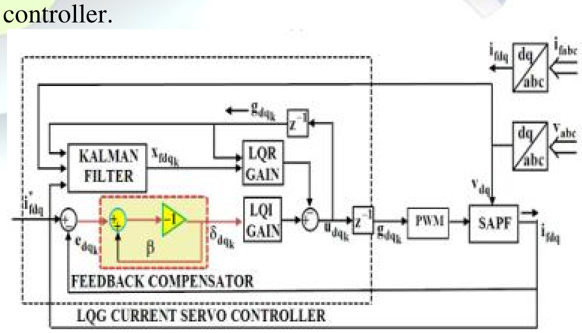

Fig. 4: Proposed LQG Servo Current Controller Strategy

1) Design of Proposed Feedback Compensator

The proposed feedback compensator plays a significant role in achieving gain stability, perfect reference tracking, less current harmonics distortion

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as well as improved bandwidth. Referring Fig.4, the output of feedback compensator is expressed by the following equation.

2) Construction of Kalman State Estimator

KF is used for measurement of harmonics [13], detection of grid perturbations [14] and estimation of fundamental component as well as system variables [15]. For linear systems contaminated with additive noise, KF is found to be an optimum estimator. In this paper, we need Kalman state estimator for LQG Servo control because we cannot implement LQ optimal state feedback without full state measurement. For implementation of the KF, one inherent computational delay is considered within the switch input udq to the SAPF system due to finite computation time and PCC voltage vdq also acts as an input to the estimator. The linear discrete-time system in dq frame can be represented as

$$x_{fdq_{k+1}} = G_{f}x_{fdqk} + S_{f}u_{fdqk} + w_{fk}$$

$$y_{fdq_k} = C_{f}x_{dq_k} + v_{fk} \quad (11)$$

Where, wfk and vfk are modeled as white noise and the associated noise covariance matrices are given by Wf and Vf . The values of matrices A, B1, B2 and C prescribed in eq (24), (25) and (26) are associated with the continuous state space model of SAPF. The state estimation by KF is formulated in two steps [16] namely predictive and update.

3) Design of Optimal State Feedback Controller

For full state feedback control design, LQR design seeks to minimize the total transfer of energy from system input to output. The associated Riccati equation solution provides the optimal state feedback controller (KLQR) that can minimize the cost function of the closed loop system given below.

$$J = \frac{1}{2}\sum_{k=0}^{\infty}\{x_{fdqk}^{T}Q_{L}x_{fdqk} + u_{dqk}^{T}R_{L}u_{dqk}\} \quad (12)$$

Where, QL is a positive semi definite matrix (state weighting matrix) and RL is a positive definite matrix (control weighting matrix). The entries of matrices QL and RL are chosen such that fastest dynamic response in SAPF system can be achieved.

4) Formulation of Proposed LQG Servo controller

The proposed LQG servo controller ensures that the filter output current of SAPF (ifdq) tracks the reference command (*ifdq) while rejecting process disturbances and measurement noise. The servo controller is the combination of optimal Kalman estimator and optimal state feedback controller and both designs are solved separately, based on the “separation principle”. The extended state space model of the proposed LQG servo controller equations according to (Fig. 2(b)) is given below:

$$x_{servo_{k+1}} = A_{servo}x_{servo_k} + B_{servo}u_{dqk} \quad (13)$$

$$y_{servo_{k+1}} = C_{servo}x_{servo_k} \quad (14)$$

$$u_{dqk} = -k_{m}x_{servo_k} \quad (15)$$

KLQI and KLQR are the linear quadratic integrator and linear quadratic regulator gains of the proposed LQG Servo controller respectively and the values of above gains can be achieved from the solutions of the state space model of LQG Servo controller.

III. FUZZY LOGIC CONTROLLER

In FLC, basic control action is determined by a set of linguistic rules. These rules are determined by the system. Since the numerical variables are converted into linguistic variables, mathematical modeling of the system is not required in FC.

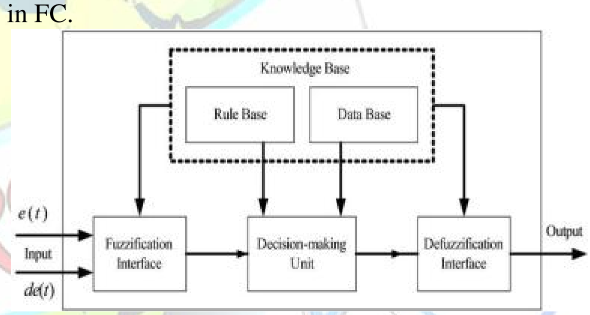

Fig.5: Fuzzy logic controller

The FLC comprises of three parts: fuzzification, interference engine and defuzzification. The FC is characterized as i. seven fuzzy sets for each input and output. ii. Triangular membership functions for simplicity. iii. Fuzzification using continuous universe of discourse. iv. Implication using Mamdani’s, ‘min’ operator. v. Defuzzification using the height method.

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TABLE I
Fuzzy Rules

Change in error	Error						
	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PM	PM	PS	Z
NM	PB	PB	PM	PM	PS	Z	Z
NS	PB	PM	PS	PS	Z	NM	NB
Z	PB	PM	PS	Z	NS	NM	NB
PS	PM	PS	Z	NS	NM	NB	NB
PM	PS	Z	NS	NM	NM	NB	NB
PB	Z	NS	NM	NM	NB	NB	NB

Fuzzification: Membership function values are assigned to the linguistic variables, using seven fuzzy subsets: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). The Partition of fuzzy subsets and the shape of membership CE(k) E(k) function adapt the shape up to appropriate system. The value of input error and change in error are normalized by an input scaling factor.In this system the input scaling factor has been designed such that input values are between -1 and +1. The triangular shape of the membership function of this arrangement presumes that for any particular E(k) input there is only one dominant fuzzy subset. The input error for the FLC is given as

$$E(k) = \frac{P_{ph(k)} - P_{ph(k-1)}}{V_{ph(k)} - V_{ph(k-1)}} \quad (16)$$

$$CE(k) = E(k) – E(k-1) \quad (17)$$

Inference Method: Several composition methods such as Max–Min and Max-Dot have been proposed in the literature. In this paper Min method is used. The output membership function of each rule is given by the minimum operator and maximum operator. Table 1 shows rule base of the FLC.

Defuzzification: As a plant usually requires a non-fuzzy value of control, a defuzzification stage is needed. To compute the output of the FLC, „height" method is used and the FLC output modifies the control output. Further, the output of FLC controls the switch in the inverter. In UPQC, the active power, reactive power, terminal voltage of the line and capacitor voltage are required to be maintained. In order to control these parameters, they are sensed and compared with the reference values. To achieve this, the membership functions of FC are: error, change in error and output

The set of FC rules are derived from

$$u=-[\alpha E + (1-\alpha)*C] \quad (18)$$

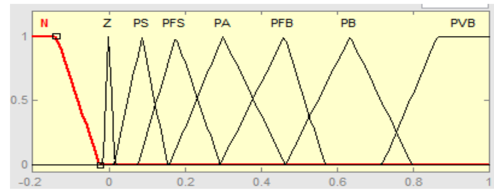

Fig 6: input error as membership functions

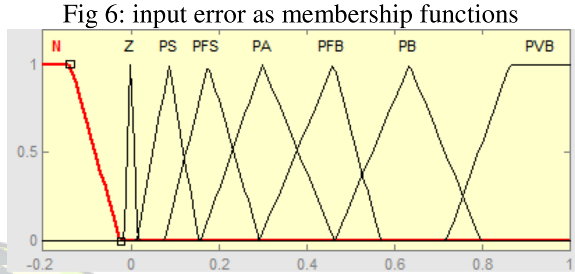

Fig 7: change as error membership functions

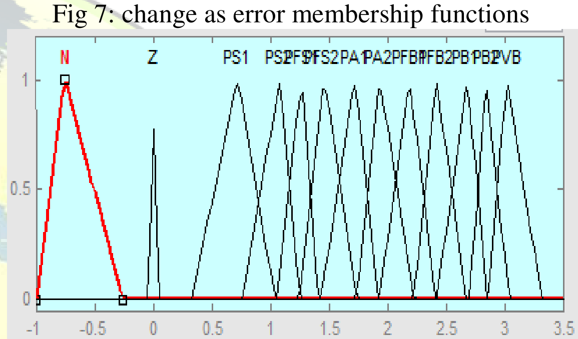

Fig.8: output variable Membership functions

Where, α is self-adjustable factor which can regulate the whole operation. E is the error of the system, C is the change in error and u is the control variable.

IV. RESULTS AND DISCUSSIONS

A simulation model for the three phase SAPF with same parameters shown in Table-II has been developed using MATLAB-Simulink.

TABLE II
SYSTEM PARAMETERS USED FOR SIMULATION

System Parameter	Supply voltage RMS line-line (V_s)=100V Supply impedance (R_s = 0.1 Ω and L_s = 0.5 mH) Supply frequency (f)=50 Hz
Load	Nonlinear Load: 3-phase diode bridge rectifier with resistive load of impedance (R=20Ω and L=10 mH) (Base Case)
SAPF	DC link capacitor (C)=2350μF; Reference DC Link voltage (v^*_{dc})=220V; Filter impedance (R_f = 0.05 Ω and L_f = 2.5 mH) Switching frequency (f_{sw}) =12.5 kHz Sampling frequency (f_s)=25 kHz

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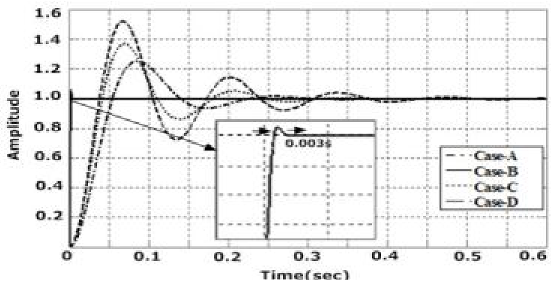
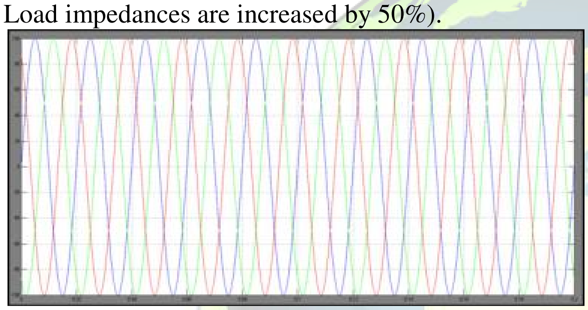
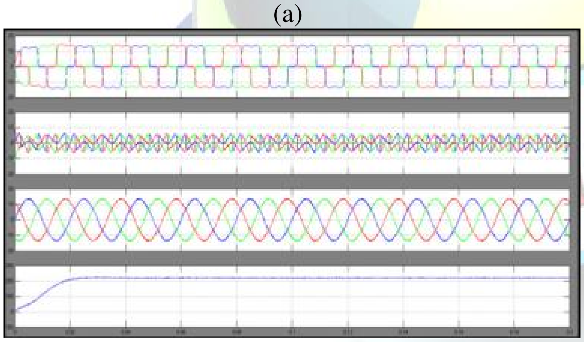


Fig.19: Step Response of the LQG Servo control system with different matrices of QL

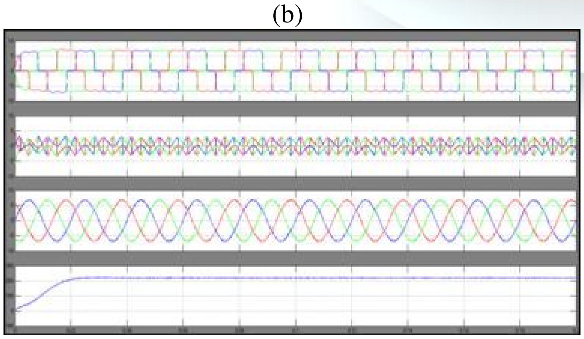
Where settling time is found to be 3 ms. Thus, QL and RL are expressed by the following eq (40). The simulation results obtained with the proposed SAPF are shown in Fig. 10 considering two Cases (Case-1: Steady-State Load Condition; Case-2: Load impedances are increased by 50%).



(a)



(b)



(c)

Fig.10: Simulation Results: (a) Waveforms of Balanced Supply voltages, (b) Response of Proposed SAPF in Case-1, (c) Response of Proposed SAPF in Case-2

The supply voltage waveforms are shown in Fig. 10(a). Fig. 10(b) presents the steady state performance of SAPF when the load impedances are kept at the base value (100%). The load current, compensating current, source current and the capacitor voltage are shown for three phases in top to bottom order. The compensated source currents are found to be sinusoidal. Similar results are found for Case-2 as seen in the respective graphs shown in Fig. 10 (c).

The robustness of proposed SAPF is analyzed here. The harmonics distortion results of the source current for phase 'a' before compensation and after compensation with proposed SAPF in both cases are given in Table II.

TABLE III
HARMONICS COMPENSATION EFFECT OF THE PROPOSED KF LQG Servo BASED SAPF (SIMULATION)

Cases	THD% of Phase-a Source Current		
	Before Compensation THD (%)	After Compensation THD (%)	Harmonics Compensation Ratio (HCR) (%)
Case-1	25.67	3.18	12.38
Case-2	21.44	2.59	12.11

This shows the robustness of proposed SAPF under parametric variations of the load. The HCR factor is calculated as follows:

$$HCR = \frac{THD\%\ After\ compensation}{THD\%\ Before\ compensation} * 100\% \qquad (19)$$

V. CONCLUSION

We presented a robust LQG Servo controller design for a SAPF. Fuzzy logic controller is used to regulate DC link capacitor voltage and to compensate harmonic current. The robustness of the proposed LQG Servo controller strategy has been verified by analyzing the performance under steady state as well as dynamic condition of power system. In addition, using the fuzzy controller for a nonlinear system allows for a reduction of uncertain effects in the system control and improves the efficiency**.** In the presence of an additive white Gaussian noise, switching noise, and distortion at PCC voltage, Kalman filter is found to be the best option involving both in reference generation and current controller realization of SAPF. The proposed reference scheme acts as a self-regulatory of dc-link voltage escaping from external linear and nonlinear controller and hence an inexpensive control strategy can be implemented. Therefore, the proposed control scheme can be an effective solution for SAPF that

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requires integrated functionalities. The compared to the conventional system, simulation results analysis reveal that the shunt active power filter performs perfectly in conjunction with fuzzy logic controller. From the obtained simulation results, the proposed SAPF has been observed to provide efficient current harmonics mitigation, reference current tracking behavior and reactive power compensation with dynamically changing load conditions (other LQR-based approaches are limited to steady-state conditions).

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