

A Fuzzy Controller Based SAPF for Power Quality Enhancement of Distribution System Integrated with Wind Energy Source

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ABSTRACT

Wind energy is emerged rapidly as the most important and viable sustainable power source due to the mature technology and wide availability. The integration of wind energy sources and utilization of nonlinear loads having different characteristics results in several challenges in a distribution system. One of which is power quality issue. Hence, in this work, the impact of power quality issues in a distribution system integrated with the wind generation system is studied in the uses of a shunt active power filter (SAPF) and presence of non-linear load conditions. The realization of SAPF is carried out using active power component theory (APCT) for reference current extraction, proportional-integral (PI) controller, and fuzzy logic controller (FLC) for dc-link voltage regulation and a basic hysteresis band current controller method for the extraction of switching pulse for operational the inverter. To enhance power quality in the proposed system, a modified fuzzy logic-controlled (MFLC) is developed to improve the transient performance of shunt APF. The proposed model is developed in MATLAB and results are given so as to show the presentation of the performance of this compensation technique in terms of mitigation of system harmonics, reactive power compensation, and enhancing the power factor.

1. Introduction

This Electrical energy has become an integral part of human life and its use is increasing globally by leaps and bounds to improve the living standard. Global concern of utilization of green and clean energy sources for sustainable power systems and shortage of fossil fuel reserves create opportunities for renewable energy sources (RES) of generation. In this manner, the expanding dangers to the earth from the vitality created by the broad utilization of fossil fuels have left us with the thought of renewable energy sources (RES) as the main conceivable arrangement. The demand for sustainable power sources has highly increased due to a lack of fossil fuel, environmental impact and global warming problems of the world. The classification and trends of wind energy technology has been discussed [1-4] in detail. Wind power is the most developing, promising, and viable sustainable power source that has been dissipated over the word, and utilization of this energy source has been expanding vary large scale. The integration of distributed generation (DG) is directed to increments in vitality productivity and a decrease in emission. The ever-increasing load demand and scarcity of electric power have attracted the attention of power engineers to

evolve the new techniques for the effective utilization of electrical energy. Such evolutions have increased the use of power electronics devices and controllers in manifold over the last two decades for more efficient operation of the electrical equipment and to transfer more power through the power networks, but they degrade the power quality in the distribution network connected with wind generation source.

The PQ problem of grid-connected wind energy conversion has been discussed [5-8] by many authors in past years. In [9], the author discussed the power quality issues related to flicker, reactive power, current harmonic distortion, stability of wind generator during the faulty conditions. Further, there are a lot of disturbances that create PQ problems such as harmonics distortion, voltage interruption, transient disturbances, frequency variations, etc. Out of these disturbances the main polluting impact will be created by harmonic distortion but at the same time, it does not mean that power conditioning is only confined to harmonic filtering. In [10], the author introduced the power electronics devices to operate on the sinusoidal voltage but they inject harmonics in the power system networks and increase reactive power demand. The injected harmonics are responsible for the distortion of voltage and current waveshapes. These nonlinear

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loads are a big reason of harmonics, and extra neutral currents in the power system network. In [11], the author reviewed the different sources of customer-generated harmonics include AC/DC converters adjustable speed drives, switching power supplies, AC phase control circuit, cyclo converters, magnetizing current of transformer, arc furnaces, welding machines, traction systems, switch-mode power supplies (SMPS), computers and programmable logic controllers (PLC's), etc. Moreover, the single-phase loads like personal computers (PCs), fluorescent lights, printers, Xerox machine, television, etc. are also responsible for excessive neutral current distribution system.

The capability and use of SAPF has been investigated in [12-14]. A SAPF could be used as the potential solution to mitigate the utility current disturbances and enhancing power quality in power distribution system integrated with wind generation system. The shunt connected custom power devices are especially useful to maintain power factor, balancing of load, limitation of harmonics and voltage regulation at distribution voltage level, etc. The SAPF operated in the current control mode is capable of injecting negative harmonic current into the grid. Hence, in today's scenario, active power is popular and preferred over the passive filter. Shunt APF has the ability to mitigate the current harmonics from the system but series has sued for voltage harmonics. In [15], the author discussed for fast and precise estimation of reference current, predictive and adaptive controllers based on the neural network have been proposed. The quick estimation of compensating currents a lot of artificial and soft computing techniques was used. Because of the added advantage of ANN to compute the Fourier series coefficient the authors have preferred this over others improved hysteresis current controller technique is overcome wide variation of switching frequency, hence, reduce the switching frequency. In [16], the author implemented a lot of on the hysteresis based current controller in literature like as adaptive frequency domain control of PWM strategy, three-dimensional PWM technique, etc.

In [17], the author developed a standalone wind-diesel hybrid system, in which an active shunt filter is introduced to mitigate the harmonics of load current. In [18-19], they are presented the recent work on the grid integration of renewable energy with SAPF for current harmonic elimination. The dc-link voltage control is achieved by either PI or fuzzy logic technique in SRF based SAPF for proposed system. In [20], the author discussed the purpose of analysis the harmonic reduction and SAPF control technique using harmonic extractor-based method to renewable energy source integrated with grid. In [21], the author proposed the SRF reference current method based shunt active power filter with PI controller to mitigate the current harmonics from the grid connected wind at PCC simultaneously non-linear load conditions. In [22], the author implemented the ICC controller is proposed for shunt active filter for enhance power quality in renewable source interfaced grid system. In [23], the author proposed the system performance parameter like output voltage, frequency and THD level at variable wind speed and nonlinear load conditions. The validity of proposed SAPF is analyzed with fuzzy logic based PWM technique. In [24], the author implemented a technique for reduce of harmonics in hybrid SAPF connected distribution network to enhance the power quality. The optimal controller was made by the improved optimization algorithm.

The recent literatures on the grid integration of wind energy with SAPF mainly focus on the study of current harmonics reduction by the grid current THD analysis. However, a smaller number of publications had been reported for proposing distribution grid level implementation of SAPF for power quality enhancement with the integration of wind energy source. Hence, there is a need to investigate the methods which may be implemented at the grid level to mitigate the power quality problem due to wind energy into the distribution grid. The performance of APC- PI theory with direct and indirect current control methods are compared and found that in both conditions, the neutral current compensation is almost same but the remarkable improvement is observed in power factor, reactive power compensation and load balancing with indirect control method. It is proved through proposed simulation that the indirect current control method performance is better than direct current control for the distribution grid integrated with wind generation system. So, proposed Indirect APC-MFLC methods are suitable to compensate harmonics and reactive power, neutral current during unbalanced loading conditions. The system is capable of maintaining unity power factor as well as sinusoidal source currents. Hence, the power quality of distribution system is improved.

The major contributions of this paper are integration and design of APCT based SAPF in proposed system for enhances the power quality problem. The proposed MFLC controller strategy is validated through APC theory by extensive simulation results for enhancement in overall power quality problem of the proposed system. This paper is classified in five sections, first is the introduction in Section 1. Section 2 mathematical modeling and detail of the proposed model and proposed SAPF control method in Section 3, simulation result and discussion presented in Section 4. The conclusion is shown in Section 5.

2. Proposed Model

A PMSG based wind energy connected through AC-DC-AC converter to distribution grid with a non-linear load connected to load bus shown in Figure 1. A shunt APF connected with the system for enhancement of power quality in non-linear loading conditions and PMSG integrated with the grid. The proposed system is not only capable of transfer the wind energy to the grid, but will also act as a shunt active power filter (SAPF) to mitigate the current harmonics and regulate reactive power feed by the nonlinear loads. Table 1 provides parameter of wind turbine and PMSG.

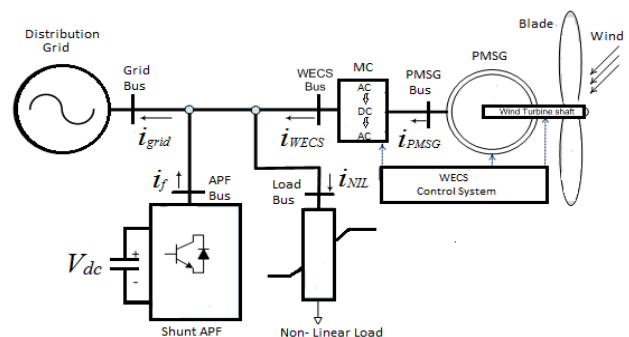


Figure 1: Block Diagram of Distribution Grid- Integrated Wind Generation System with Shunt APF and Non-linear Load.

A. Modeling of Wind Turbine System

The wind speed is sum of these components.

$$V_w(t) = V_B(t) + V_N(t) + V_G(t) + V_R(t) \quad (1)$$

where, V_w is the wind speed, all of them in “meter/ second” and time t is in “second Here this wind speed signal have four component, i.e. the basic speed of wind (V_B), a fluctuating wind (V_N) that describes a steady increase in wind speed, gust component (V_G) and a gradient wind component (V_R). The mechanical energy given wind turbine is determined as follow [3]

$$P_{wind} = \frac{1}{2} C_p(\lambda, \beta) \pi r^2 \rho_{air} V_w^2 \quad (2)$$

Power coefficient (C_p) is the ratio of mechanical power generated by the turbine to the power available in the wind. Which λ is the tip speed ratio, C_p is given as [3]

$$C_p = c_1 \left(c_2 \frac{1}{\alpha} - c_3 \beta - c_4 \beta^x - c_5 \right) \quad (3)$$

β is a function of the pitch angle of rotor blades, when β is equal to zero.

$$\frac{1}{\alpha} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1 + \beta^2} \quad (4)$$

Therefore, the tip speed ratio can be given as [3]

$$\lambda = \omega_a r / V_w \quad (5)$$

The mechanical torque turbine is defined as follow [3]

$$T_{mech} = \frac{0.5 C_p \pi r^2 \rho_{air} V_w^2}{\omega_a} \quad (6)$$

The driven train is treated as one concentrated mass model to time efficiency and precision. It is defined as:

$$\frac{d}{dt} \omega_a = \frac{1}{j} (T_{mech} - T_{elect} - B_x \omega_a) \quad (7)$$

where, B_x is damping coefficient, ω_g is angular speed (rad/sec), T_{elect} is the electromechanical torque (Nm), T_{mech} is the aerodynamic torque and J equivalent rotational inertia of the generator (kg-m²)

B. Modeling of PMSG

The direct axis and quadrature axis voltage equation of generator is define as

$$V_d \equiv -R_s i_d - L_d \frac{di_d}{dt} + \omega_e L_q i_q \quad (8)$$

$$V_q \equiv -R_s i_q - L_q \frac{di_q}{dt} - \omega_e L_d i_d + \omega_e \mu_g \quad (9)$$

ω_e is the rotor speed in rad/s of the generator, describe by

$$\omega_e = \omega_a P \quad (10)$$

The electromagnetic torque of PMSG is given by

$$T_{elect} = \frac{3}{4} P [\mu_g + (L_d - L_q) i_d] i_q \quad (11)$$

Then, the angular speed of generator is defined as [4]:

$$\frac{d}{dt} \omega_a = \frac{1}{j} (T_{mech} - T_{elect} - B_x \omega_a) \quad (12)$$

Table 1: parameter of wind turbine & generator

Parameter	Value
Generated Power, (P)	2 MW
Stator Resistance (R_s)	0.7305 mΩ
Stator d-axis Inductance (L_d)	1.21 mH
Stator q-axis Inductance (L_q)	2.31 mH
Permanent Magnet Flux (μ_g)	6.61 Wb
Inertia (J_{eq})	10000 kg.m ²
Radius of Blades (r)	38 m
Air Density (ρ)	1.205m ³

3. Proposed Control Method for SAPF

The Voltage Source Inverter has seen widely utilized in shunt APF setup to minimize power quality issues. It is also utilized for energy storage during ideal system conditions, but the charging and discharging of this capacitor controlled utilized a control theory. Hence, only the active filter fit for producing counter harmonic current and feeding the reactive power to point of common coupling (PCC). Figure 2 presents the configuration of the proposed shunt APF with a distribution system integrated into the wind energy conversion system (WECS). The main aim of proposed method is to evaluate the control strategy for current harmonics reduction, compensation of reactive power and balancing of load current at PCC when the supply current is distorted.

3.1. Active Power Component (APC) or Unit Vector Template Theory

Shunt APF can effectively handle the harmonics and reactive power problems simultaneously. Presently shunt APFs are designed to encounter all the harmonics which is generated by nonlinear loads but the distribution system is highly unbalanced, so it is required to mitigate the neutral current burden and make the source current sinusoidal for the calculation of the desired compensation current. The unit vector templates are determined as

$$\begin{aligned} U_a &= \frac{v_{sa}}{V_{SP}} = \sin\theta \\ U_b &= \frac{v_{sb}}{V_{SP}} = \sin(\theta - 120^\circ) \\ U_c &= \frac{v_{sc}}{V_{SP}} = \sin(\theta + 120^\circ) \end{aligned} \quad (13)$$

In a three-phase system, it is represented as i_a^* , i_b^* , and i_c^* . Neutral current ought to be zero, along these references neutral current taken as zero in a balanced system. Capacitor voltage error goes

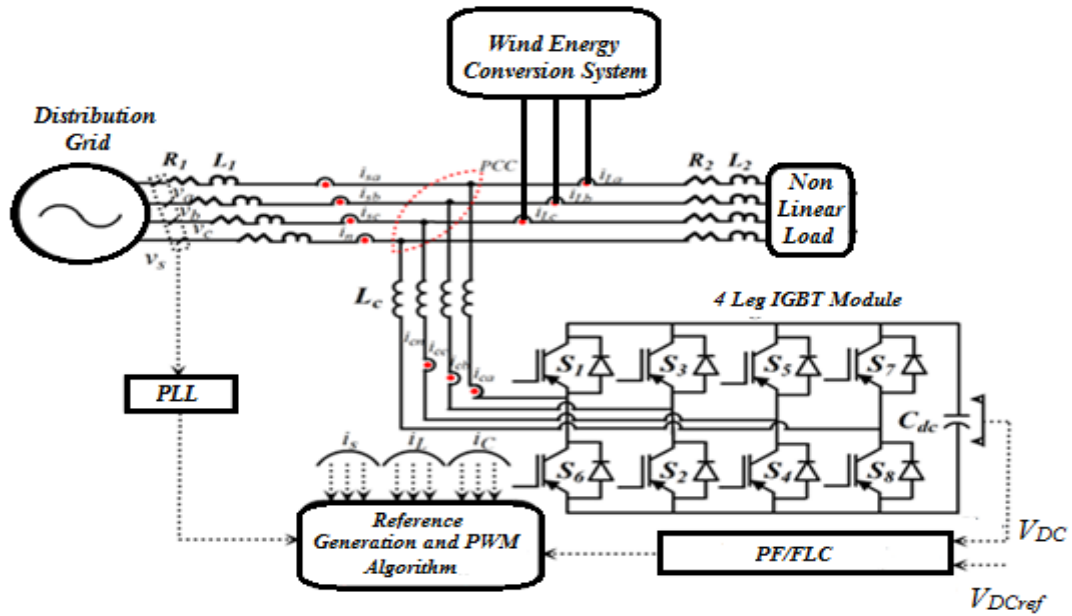


Figure 2: Proposed Shunt APF Configuration with Distribution System

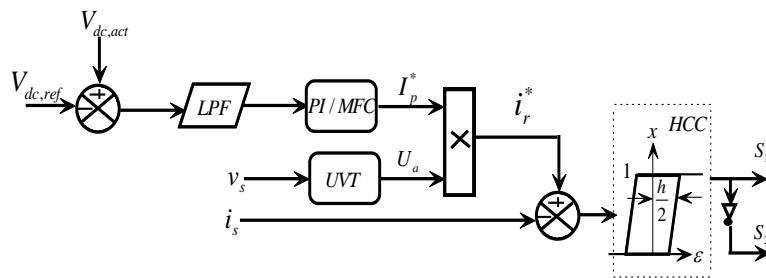


Figure 3: Block Diagram of UVT/APCT Algorithm with Indirect Current Control Method

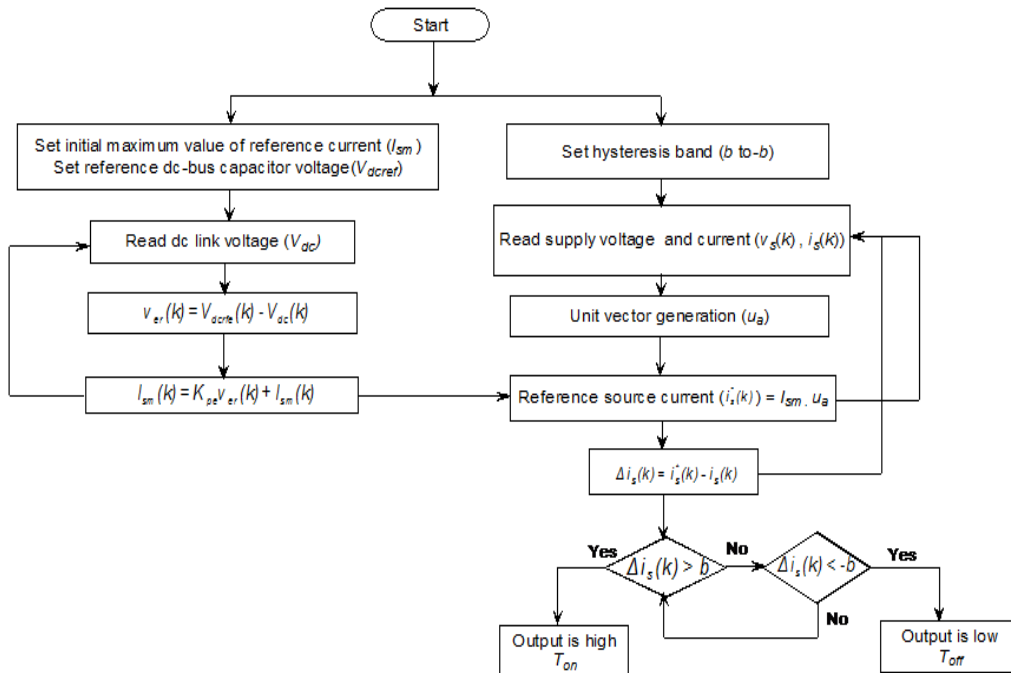


Figure 4: Flowchart of Active Power Component Theory (APCT) Algorithm

through the low power filter. The filtered dc voltage is contrasted with the reference value. Reference current can be composed as

$$i_a^* = I_m U_a, \quad i_b^* = I_m U_b, \quad i_c^* = I_m U_c, \quad i_n^* = I_m U_n \quad (14)$$

As present in the Figure 3 that capacitor voltage error goes through the LPF, which remove the high-frequency ripple from the voltage. This filtered dc voltage is compared with the reference value. Now error between the reference and grid current is processed by utilizing the following equations

$$\left. \begin{aligned} i_a^* &= I_m U_a \\ i_b^* &= I_m U_b \\ i_c^* &= I_m U_c \\ \text{and} \\ i_n^* &= I_m U_n \end{aligned} \right\} \quad (15)$$

Figure 4 presents the flowchart of the APCT algorithm with indirect current control method.

3.2. DC voltage Controller

DC voltage controller calculates response of the model and increasing proportional above a value can generate swaying. Integral control expels the error from the output. To actualize the PI controller, the dc link voltage is estimated the reference value. The transfer function of the PI-controller is given from [18] as follows

$$H(s) = (k_i/s) + k_p \quad (16)$$

For the usage of the fuzzy rule over the PI controller in close loop filter, the dc voltage signal is compared with reference signal and reference error will be produced as follow [18]:

$$e = V_{dc, reference} - V_{dc, actual} \quad (17)$$

The reference for nth sampling time is taken as a change of error in fuzzification process is determining as follows [18]-[19]

$$C_{e(n)} = e(n) - e(n-1) \quad (18)$$

3.3. Proposed Fuzzy Logic controller

The proposed modified fuzzy logic controller (MFLC) of the system is used to control the response of the dc voltage. They can be defined, as

$$x = (x_i, U_i, \{T_{x_i}^1, T_{x_i}^2, \dots, T_{x_i}^{k_i}\}, \{\mu_{x_i}^1, \mu_{x_i}^2, \dots, \mu_{x_i}^{k_i}\}) \quad (19)$$

for $i = 1, 2, \dots, n$

$$y = (y_i, V_i, \{T_{y_i}^1, T_{y_i}^2, \dots, T_{y_i}^{l_i}\}, \{\mu_{y_i}^1, \mu_{y_i}^2, \dots, \mu_{y_i}^{l_i}\}) \quad (20)$$

for $i = 1, 2, \dots, m$

where x & y is the input & output linguistic variable form a fuzzy output space. The size of a term set, $T_{(xi)} = K_i$ is called as the fuzzy partition number of X_i . In the case of a two – input-one-output proposed MFC system, If $T_{(x1)} = 9$ and $T_{(x2)} = 9$, than the number

of fuzzy control rules is 9×9 . A bell shaped relationship function has been used.

$$\mu_{x_i}(x) = \exp\left(-\frac{(x - m_i)^2}{\sigma_i^2}\right) \quad (21)$$

This modified fuzzy controller rules are developed and approved dependent on AND Boolean logic operator. The new rules are characterized by fundamental stability position and moment in time response. To use of fuzzy sets, we restructure operators of the standard set method to fit the particular relationship functions of fuzzy logic for a value between zero & one. Here two variables are utilized as a contribution of MFLC, first is Error E and second change of error C_e . The moment in time response has been divided into four regions A_1, A_2 , and A_3, A_4 with two arrangements of point, first is the peak value index (b_1, b_2), and second cross over-index (c_1, c_2). The fuzzy operator AND is formed from a grouping of fuzzy prepositions. Based on the above theory, rules are defined as ZE, PN NB, NS NM, PS, PB, and PB, PM for processing the dc-link response shown in Table 2. Figure 5 shows the moment in time response of a stable closed loop-system.

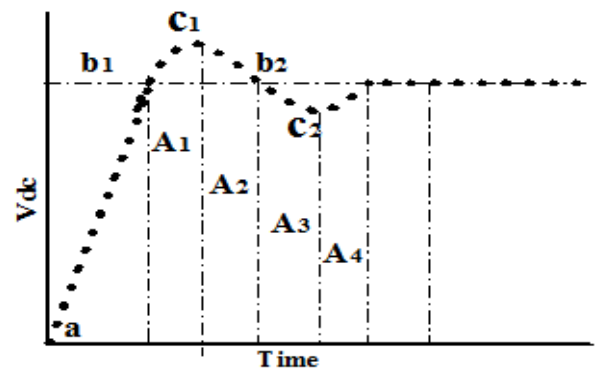


Figure 5: Moment in Time Response of a Stable Closed Loop System.

Table 2: Mechanism of Proposed modified fuzzy rule

Error/ Change error (E)/(Ce)	NB	NM	NS	NN	ZE	PN	PS	PM	PB
NB	NB	NB	NB	NB	NB	NB	NB	NM	ZE
NM	NB	NB	NM	NM	NM	NM	NS	ZE	PM
NS	NB	NM	NM	NS	NS	NS	ZE	PS	PM
NN	NB	NM	NS	NN	ZE	ZE	PS	PM	PB
ZE	NB	NS	NS	ZE	PN	PN	PS	PM	PB
PN	NS	NB	NS	PN	PS	PS	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PS	PM	PM	PB
PM	NB	ZE	PS	PM	PM	PM	PM	PB	PB
PB	ZE	PM	PB	PB	PB	PB	PB	PB	PB

4. Result and discussion

The performance analysis of the distribution grid integrated with wind generation system is study with proposed SAPF under the use of different controllers for unbalanced loading condition. The impact of PQ issues in a distribution grid integrated with wind generation system is investigated in the presence of SAPF. The effectuation of SAPF is carried out using active power component theory (APCT) for reference current generation with direct and indirect current control method. Proportional integral (PI) controller is proposed with modified fuzzy logic controller (MFLC) for dc link voltage regulation and a basic hysteresis band current controller method. For study state analysis purposes, the load change with an increase at $t=1.2$ sec, and again it is changed with decreasing at $t= 2.3$ sec. The RMS load current at $t=0.2$ sec is in phase “a” 139.2 Amp, phase “b” 103 Amp, and in phase “c” 68.8 Amp. This result presents the unbalanced condition in the distribution system. Without compensation the neutral current flow in 73.3 Amp, the reactive power drawn is 20 kVAR, power factor degradation is below 0.8, and load current THD is 22.50%. A SAPF with a hysteresis-based APC technique is used to enhance the performance of the system according to certain power quality standards. In this technique, the reference signal is compared with actual utility load current.

4.1. Case 1: Direct current control with APCT-PI

In the direct current control method with APCT-PI, the switching pulses are generated through hysteresis controller by comparing the sensed three phase shunt APF current with their computerized generated reference current signal. The performance of the direct current control method with the APCT technique as shown in figure 6. The following observation has been made out after compensation reactive power flow between source and load is 7 KVAR, natural current is around 7 Amp and system power factor is nearly 0.94.

4.2. Case 2: Indirect current control with APCT-PI

In the indirect current control method, the PWM switching pulses are obtained by comparing the sensed three phase current with their reference current which are generated by the reference current extraction methods. The performance of the in-direct current control method with the APCT technique is shown in figure 7. The following observation is made out after compensation reactive power flow between source and load is 6 KVAR, natural current is around 6.8 Amp and system power factor is nearly 0.996. Hence the performance of the in-direct current control loop with unit vector template theory is found better than direct control so modified FLC implanted on indirect current method.

4.3. Case 3: Indirect current control with Modified Fuzzy Logic controller with APCT

It provides the batter result in a comparison of harmonics mitigation, reactive power compensation, and power factor improvement. From the figure 8, following observation, has been made out after compensation reactive power flow between source and load is 3.7 KVAR, natural current is around 4.7 Amp and system power factor is nearly 0.999. Hence the performance of the in-direct current control loop with MFLC based APC theory

is found suitable for SAPF. The comparisons of harmonics mitigation are shown in figure 9.

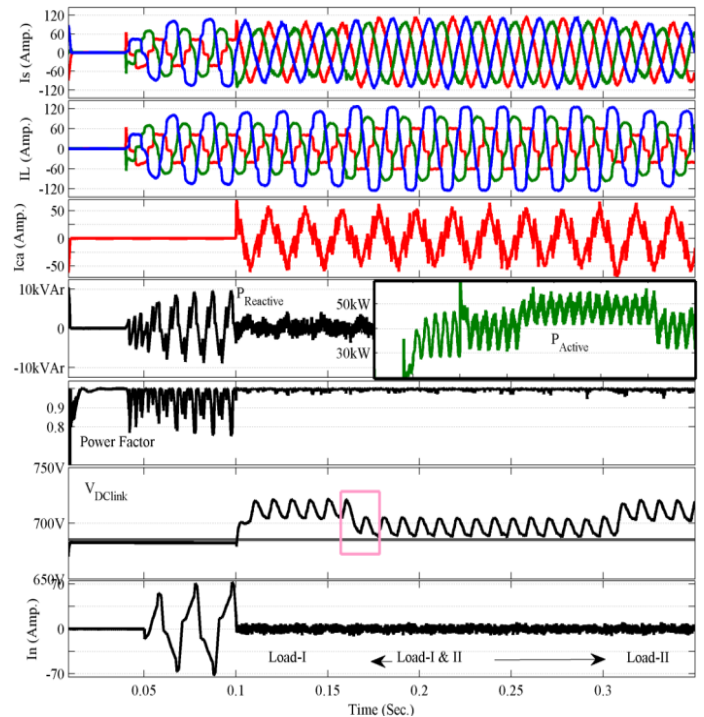


Figure 6: Indirect current control method shown as I_{source} , I_{load} , $I_{neutral}$, $P_{react.}$, PF, V_{DC} and I_n with APC-MFLC theory.

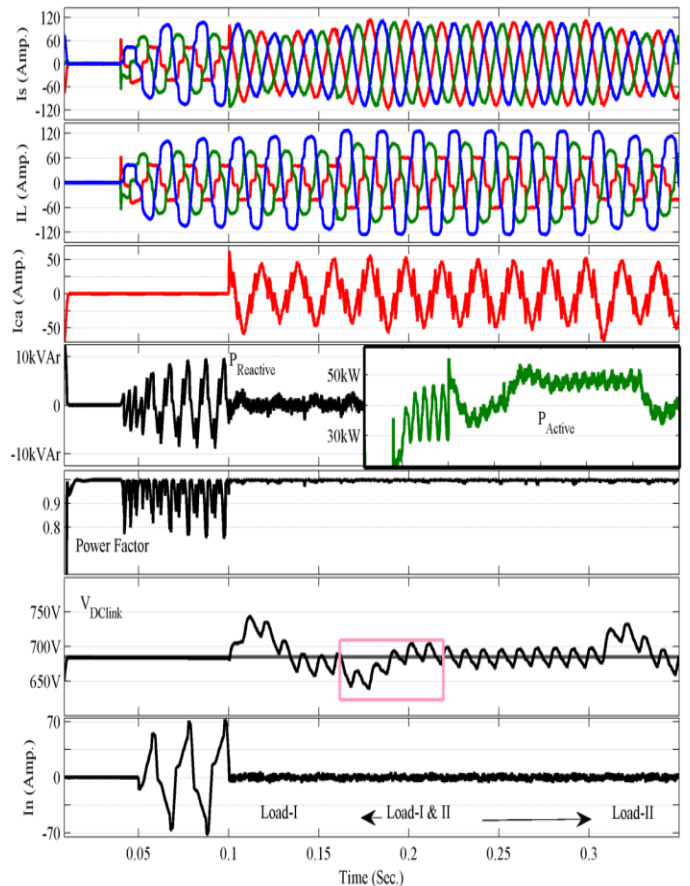


Figure 7: Direct current control method shown as I_{source} , I_{load} , $I_{neutral}$, $P_{react.}$, PF, V_{DC} and I_n with APC-PI theory.

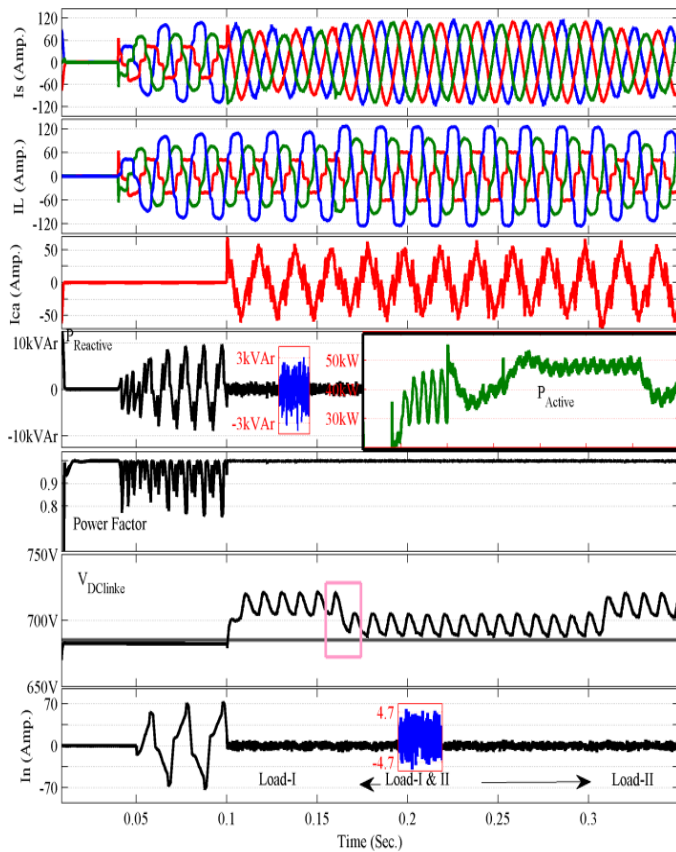


Figure 8: Indirect current control method shown as I_{source} , I_{load} , $I_{neutral}$, P_{react} , PF, V_{DC} and I_n with APC-MFLC theory.

4.4. Performance comparison of direct APC-PI, Indirect APC-PI and Proposed Indirect APC-MFLC

The comparison of overall performance of proposed system are discussed in Table 3. The performance of APC- PI theory with direct and indirect current control methods are compared and found that in both conditions, the neutral current compensation is almost same but the remarkable improvement is observed in power factor, reactive power compensation and load balancing with indirect control method. It is proved through proposed simulation that the indirect current control method performance is

better than direct current control for the distribution grid integrated with wind generation system. So, proposed Indirect APC-MFLC methods are suitable to compensate harmonics and reactive power, neutral current during unbalanced loading conditions. The system is capable of maintaining unity power factor as well as sinusoidal source currents. Hence, the power quality of distribution system is improved.

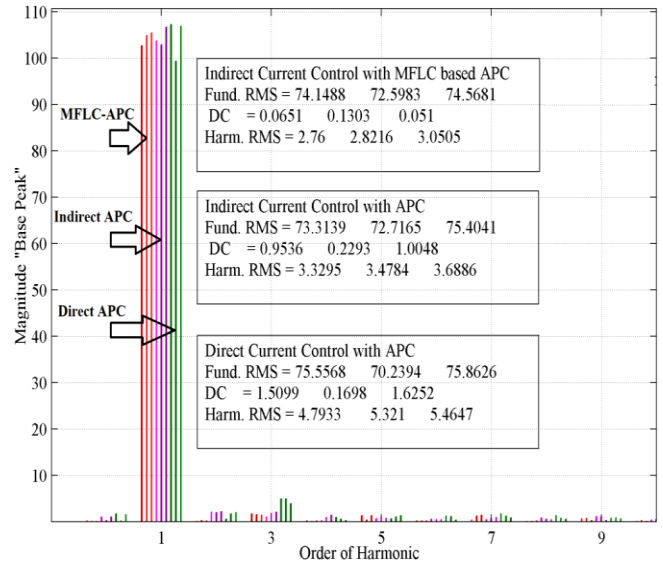


Figure 9: THD with Direct APCT-PI, Indirect APCT-PI & Indirect APCT-MFLC.

5. Conclusion

This paper presents a SAPF based on APC theory for reference current generation and proposed MFLC method for dc-link voltage control to enhance power quality of the distribution grid integrated with wind energy source under non-linear load. The performance of APC theory with direct and indirect current control methods is compared and found that in both conditions, the neutral current compensation is almost the same but the remarkable improvement shown in power factor, reactive power compensation, and load balancing with the indirect current control method.

Table 3: Comparison of direct APCT-PI, Indirect apct-pi and indirect Apct-MFLC

Parameter	Direct control with APCT			Indirect direct control with APCT			Indirect direct control with MFLC- APCT		
	I_{sa}	I_{sb}	I_{sc}	I_{sa}	I_{sb}	I_{sc}	I_{sa}	I_{sb}	I_{sc}
Balancing of source current I_s	108.4	98.06	105.1	103.6	102.8	106.6	110.8	1.8.1	108.1
Harmonic RMS after comp.	4.793	5.321	5.464	3.329	3.478	3.688	2.760	2.821	3.050
Neutral current I_n after amp.	7.0			6.8			4.7		
Reactive power after comp. (kVAr)	7			6			3.7		
Power Factor (PF)	0.94			0.996			0.999		

Hence, it has been proved through a simulation study that the indirect current control loop performance is better than the direct control loop for the unbalanced distribution system. The performance of the proposed method using APC-MFLC based realized SAPF is compared to that of SAPF designed based on reported strategies such as direct APC-PI controller and indirect APC-PI controller. The simulation results show the effectiveness of the proposed control algorithms to mitigate the harmonics, compensate the reactive power, and neutral current and to improve power factor with the balancing of source current using the MATLAB/Simulink. Finally, the proposed algorithms are capable of improving power quality problems in the distribution system with wind energy sources under non-linear load.

Conflict of Interest

All authors declare no conflicts of interests.

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