

Advanced compensation scheme for enhancing photovoltaic power quality

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ABSTRACT

With the photovoltaic (PV) system becoming highly popular in distribution network, there is also a growing concern regarding its adverse impacts over the power quality (PQ) of integrated system. This deterioration in PQ has sparked a new interest in the filtering techniques used in the power system for mitigating these problems. In contrast to conventional passive filters now active power filters (APFs) are being looked as the predominant solution. This paper presents a state-estimation based effective compensation strategy for enhancing performance of employed APF scheme. A novel control technique for PQ enhancement is proposed where Kalman filtering approach has been applied for generating the reference signals. Also, an adaptive hysteresis band technique has been applied here in the switching strategy. Thus an enhanced filter performance is achieved with reduced complexity and better elimination of distortions. Simulated results obtained in MATLAB/Simulink platform have been analyzed completely, where the superiority of filtering algorithm has been also demonstrated through least total harmonic distortion (THD) achieved in source current among all the existing Kalman filters.

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1. INTRODUCTION

The latest advancements in photovoltaic technology like reduced panel costs, higher efficiency and improved tracking schemes have provided a driving thrust resulting in enormous photovoltaic (PV) penetration [1]-[4]. However, there also exists another face of this growing trend which needs to be addressed for successful and effective utilization of these integrated systems. In addition to all the PV advantages [5]-[7] there have been rising issues also like deterioration in system reliability, transient stability, and power quality [8]-[11]. In general, PV system interfacing is carried through a current controlled voltage source inverter (VSI) with frequent switching on and off [12]-[14]. Also, the non-linear loads mainly draw distorted currents and hence generates large amount of harmonics in the system [15]-[17]. Another important concern is that sudden tripping of PV system may lead to voltage transients and other ill-effects [18], [19]. Thus it can be seen that PV penetration leads to a number of power quality (PQ) issues which may cause serious damage if not addressed properly. Nowadays, standards and regulations are imposed to maintain the PQ parameters at point of common coupling (PCC). Optimal PQ is the essential requirement from both technical and economical aspects. Therefore, the implementations of innovative and cost-effective compensation techniques are needed. Traditional approach has been to use passive filter [20] to suppress harmonics in the current and to counter other PQ problems. These offer a low impedance circuit for the high frequency

harmonics, thereby, permitting only fundamental components to be injected while attenuating the ripples. But there are major issues associated with passive filter like sensitivity to variation in impedance or frequency, and failure to filter properly when conditions get unbalanced. [21].

Hence, nowadays compensation methodologies implemented by using high speed power electronic devices are being looked upon as effective remedial for PQ issues. To mitigate the PQ problems, active power filters (APFs) with various control strategies are now being focused as the promising solution, capable of resolving the significant issues like harmonic distortions and unbalance [22]-[24]. Unlike passive, APFs are adaptable to rapidly changing source impedance and provide the necessary harmonic compensation for varying non-linear loads. These APFs generate the compensating component of current or voltage and hence cancels out the original harmonics content [25].

Therefore, in order to address all the aforesaid issues, this paper presents a modified perspective of Kalman filtering which offers robustness against modeling uncertainties and achieves enhanced sensitivity towards grid perturbations with reduced tuning efforts. Here, lagging nature of the existing recursive Kalman filters has been modified by introducing a weighted matrix which advances the estimated values of state variables in one step. Thus an enhanced filter performance is achieved with reduced complexity and better elimination of harmonic distortions. The superiority of the proposed modified filtering approach has also been assessed by comparing its harmonics mitigation capability with those of various existing Kalman techniques [26]. Thus this work presents the application of advance control scheme for APF topology for elimination of harmonics to bring down the distortion level for PV integrated system.

2. APF TOPOLOGIES FOR ELIMINATION OF HARMONICS

Due to the switching action of converters and increased applications of non-linear loads, the integrated PV systems do not draw a sinusoidal current at PCC. This non-sinusoidal current may also distort the voltage waveforms and lower the power factor due to the flow of harmonics. APFs basically inject the compensating current or voltage depending upon the way they are connected in the network. This injected current or voltage is in phase opposition with the actual quantity and thus compensates for the harmonics. A number of factors like cost, integration and applicable harmonic filtering standards by the utility, need to be considered for deciding the filter configuration. As per the required applications or the electrical parameter to be compensated, APFs can be employed in shunt or series topology as discussed.

2.1. Shunt APF

It is the most common topology of APF where the switching device is connected in parallel. As shown in Figure 1, its behavior is similar to that of current source as it injects a current with 180° phase-shift at PCC. It consists of a voltage source converter (VSC) with pulse with modulation (PWM) controller and a control strategy for generating reference signal for the filter current, which is then processed by PWM controller for switching of VSC. The conduction and switching losses of VSC is provided by a connected capacitor.

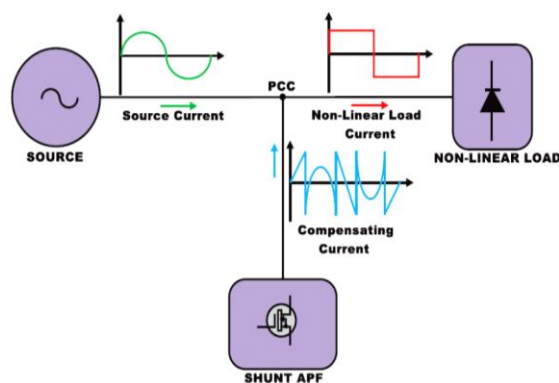


Figure 1. Compensating current injected by shunt APF

2.2. Series APF

Basically the series APF performs the isolation work by presenting very high impedance for the harmonics. It introduces a compensating voltage in series with that of source, having same magnitude but in phase opposition to that of harmonic components and thus cancels the voltage harmonics. Figure 2 shows the

basic topology of a series APF. Similar to shunt APF, it also consists of a VSC with a PWM controller and a control strategy for generating reference signal for the compensating voltage, which is then processed by PWM controller for the switching of VSC. These series APFs can be used in systems that supply power to the voltage sensitive devices, requiring a pure sinusoidal voltage source.

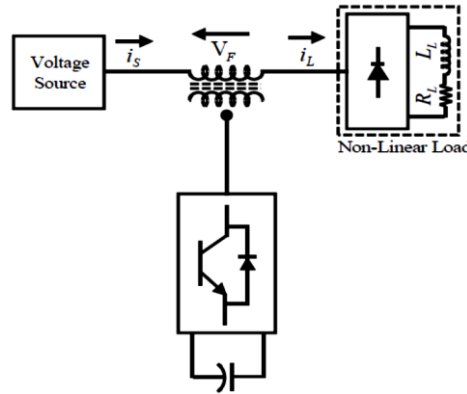


Figure 2. Configuration of series APF

3. APPLIED CONTROL ALGORITHM FOR APF

For mitigation of PQ issues, designing the proper control strategy is the core aspect of APF scheme. There are two main functional parts. Of this control unit described below in details:

3.1. To generate or estimate the reference source current

This control scheme basically senses the voltage or current signals and hence generates reference current by means of distorted waveforms. Thus it is commonly known as harmonic extraction technique. In this research work a robust control scheme employing Kalman filtering with recursive loop has been proposed for estimating the reference current. The applied synchronous reference frame (SRF) approach for transformation is illustrated through the block diagram as shown in Figure 3. It basically transfers the stationary co-ordinates to the synchronously rotating d-q axes through Park’s transformation. Then after processing the signals, controller finally generates the reference currents back in stationary co-ordinates employing the inverse transformation.

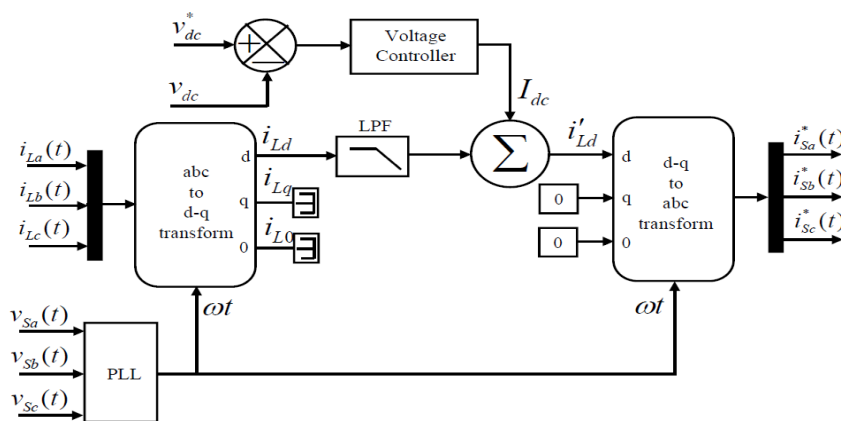


Figure 3. Applied control strategy for reference estimation

3.2. To generate switching signals or gate pulses for VSI

This is the second important aspect of controller and commonly known as current modulation scheme. This basically governs the value and shape of compensating component by generating gate signals for switching of inverter. Among the various controllers, adaptive hysteresis band (HB) technique is applied

here which gives advantages like fast controllability, accuracy, simplicity and robustness. Applied method compares the reference current with the actual to generate the error current, which is then made to pass through a preset hysteresis band. Thus that particular switch is turned off whose limit is exceeded and hence HB controller forces tracking within the band limit as shown in Figure 4.

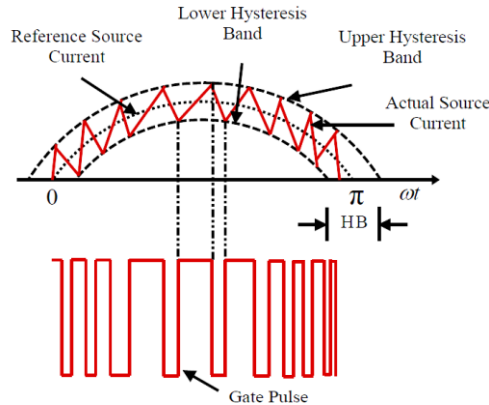


Figure 4. Pattern of switching in applied HB scheme

4. METHODOLOGY FOR PROPOSED APF SCHEME

The circuit arrangement incorporating all the controllers for APF scheme is shown in Figure 5. The basic function of Kalman filtering lies in the calculation of amplitudes for electrical quantity from the sample which results in the formation of a vector for system state. However, we can prevent the intermittent lagging nature of recursive filtering by modifying and introducing a predictive loop in Kalman filter (KF).

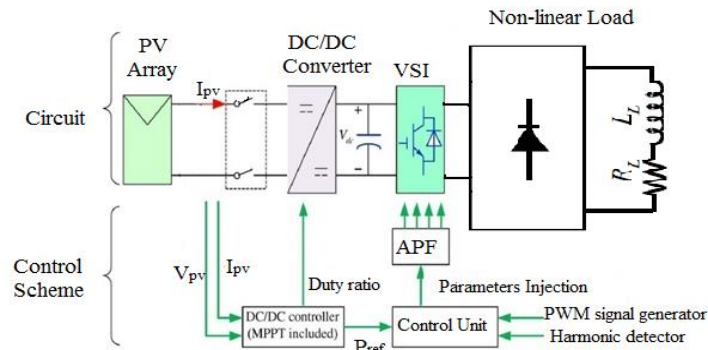


Figure 5. APF control scheme for mitigating PQ issues

For any Kalman filter with recursive loop, the following equations describe the system with two noises: one being process noise and other measuring noise.

$$x(k) = \phi x(k - 1) + w(k - 1) \tag{1}$$

$$z(k) = Hx(k) + v(k) \tag{2}$$

These expresses first-order auto regressive process where (1) is the modeling of signal and (2) is the observation equation. Here, $x(k)$ represents state variable vector at k th instant, ϕ represents matrix for state transition, $w(k)$ is the noise processing vector, $z(k)$ represents measurement of signal, H constitutes matrix for observation whereas $v(k)$ is the measurement noise vector. For the present sample each of its state variables is estimated as given by (3).

$$\hat{x}(k) = \Phi\hat{x}(k - 1) + K(k)[z(k) - H\Phi\hat{x}(k - 1)] \tag{3}$$

Where, $K(k)$ is the corresponding Kalman gains vector for each of the variables which adjusts the least square estimations and it is given as (4).

$$K(k) = P(k/k - 1)H^t[HP(k/k - 1)H^t + R(k)]^{-1} \tag{4}$$

where, the weighted matrix corresponding to "k" th instant covariance is represented by $R(k)$. The complete filter processing for signals generation has been illustrated in details through block diagram shown in Figure 6. It can be seen here that two estimators are incorporated where one estimates the current and other the voltage. On the basis of state vectors estimation of harmonics is carried out for each of samples. The instant value of quantity is compared with the reference value to estimate the error which represents weight matrix that corresponds to instant covariance. Finally passing this error signal through adaptive band generates the required gate signal.

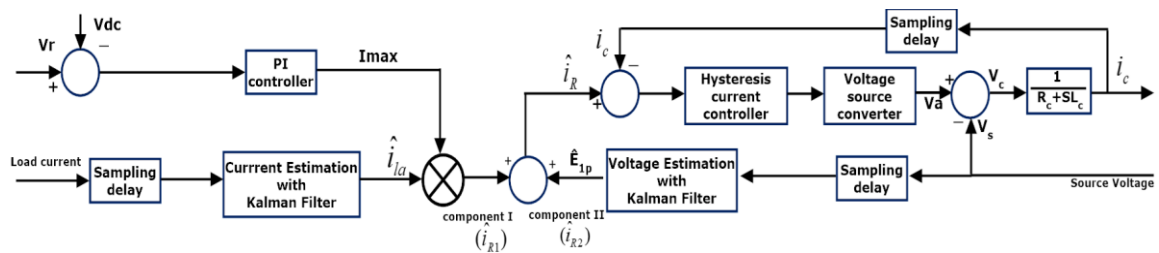


Figure 6. Applied control unit for APF

5. RESULTS AND DISCUSSION

Simulated results for active power filter compensation algorithm are obtained in MATLAB/Simulink platform. The in-phase frequency components generated by Kalman filtering are used for producing the reference current. The non-linear load constituted with diode bridge rectifier has a resistance of 20 Ω and inductance of 10 mH. First the source voltage waveform with peak value of 230 V is shown in Figure 7. When this voltage is fed to the system of non-linear load without any APF compensation scheme, then the load draws a highly distorted current as shown in Figure 8. The same distortions are reflected towards source side as at present load current is same as source current when no filtering is applied.

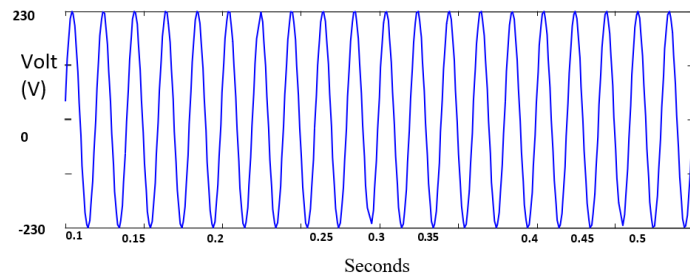


Figure 7. Sinusoidal source voltage

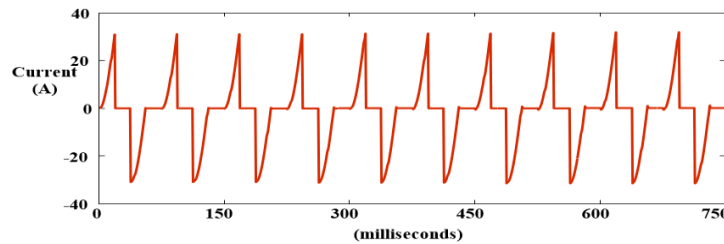


Figure 8. Un-compensated distorted source current

Consequently, the fast fourier transform (FFT) analysis of source current gives out a high percentage of harmonics at present. As shown in Figure 9, THD of current reaches to a high value of 29.3% which definitely has to be filtered out with applied APF controller. Now on applying the APF compensation strategy the compensating current i_c is injected successfully in opposite phase for the cancellation of harmonics. Therefore, harmonic components are cancelled out by this compensating component and only the sinusoidal output is obtained for the filtered source current. Figure 10 shows all three different types of currents on the same graph. It can be clearly observed that after injecting this compensating current source current differs from load current now and hence distortions are not reflected on source side now. This transition in source current from distorted to sinusoidal on being subjected to applied filtering scheme is shown in Figure 11. Also, the effectiveness of APF algorithm is demonstrated through FFT analysis shown in Figure 12. Here, it depicts the capability of filtering algorithm for efficient enhancement in power quality as THD of the source current after compensation is brought down to a mere value of 1.96%. Further, to validate the distinct effectiveness of this proposed modified KF algorithm, here a comparison of THD is made as obtained in other KF based algorithms. Referring to detail analysis given in [26], a comparative chart of THD for different existing KF based techniques has been summarized in Table 1. It is found that least THD is achieved with the modified KF algorithm proposed here in this paper. Thus it depicts the enhanced performance of proposed algorithm, where in addition to features like reduced complexity and increased sensitivity, a superior capability of eliminating harmonic distortions is also achieved as a major advantage.

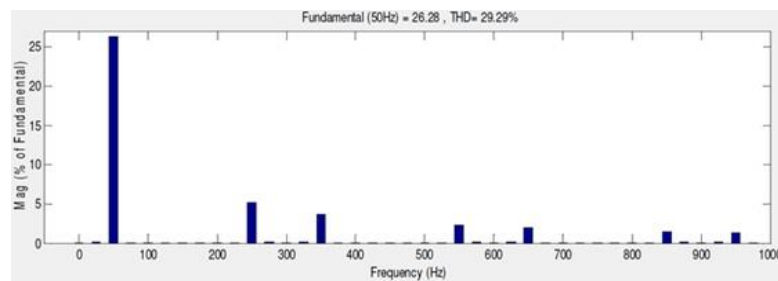


Figure 9. FFT analysis for un-compensated current

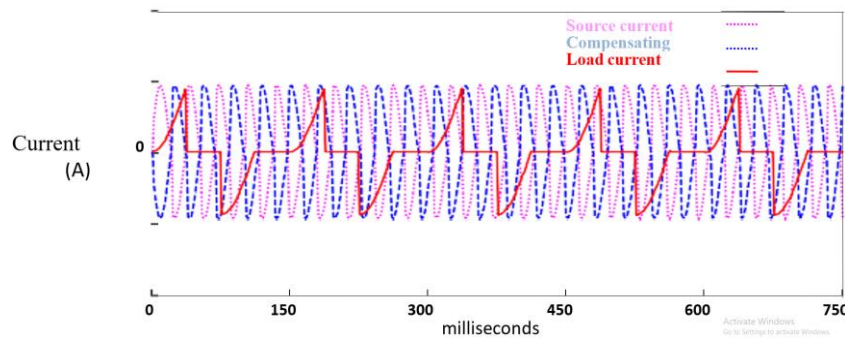


Figure 10. Injected compensating current component

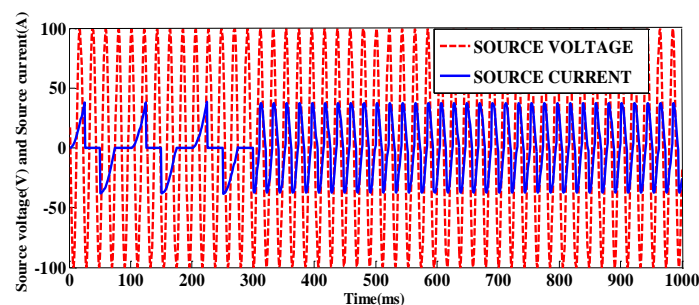


Figure 11. Effectiveness of applied controller in filtering distortions

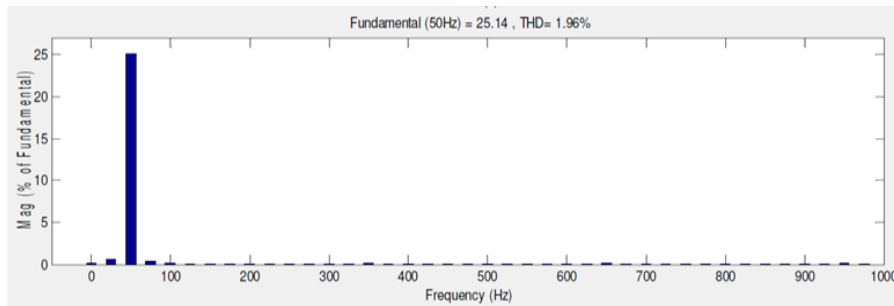


Figure 12. FFT analysis of filtered source current

Table 1. Comparison of compensation capability of different Kalman algorithms

S.No.	Compensation Algorithm	THD after compensation
1	General KF	4.79%
2	Extended Kalman filter (EKF)	4.92%
3	Robust extended Kalman filter (REKF)	4.63%
4	Robust extended complex Kalman filter (RECKF)	4.46%
5	Modified KF(Proposed here)	1.96%

6. CONCLUSIONS

In this paper PQ issues for PV system penetrations have been addressed. The proposed APF control scheme has applied modified Kalman filter for the estimation of reference current which overcomes the deficiencies of earlier KF based approaches. Here, the introduction of a weighted matrix advances the estimation of state variables and hence the proposed algorithm achieves the advantageous features like reduced tuning effort, enhanced sensitivity and reduced computational burden. Also, adaptive hysteresis controller is applied for pulse generation, which does not have a fixed band and adaptively varies with system parameter. Detailed performance analysis of proposed control algorithms have been done in MATLAB/Simulink platform, where the effectiveness of filtering technique has been illustrated. The enhanced filtering performance has been also signified by comparing the harmonics elimination capability of various KF algorithms. The proposed APF scheme is found to be most effective for eliminating distortions in the source side where least THD is resulted having low value of 1.96% only.




REFERENCES

- [1] R. H. G. Tan, C. B. Chuin, and S. G. Solanki, "Modeling of single phase off-grid inverter for small standalone system applications," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 11, no. 3, p. 1398, Sep. 2020, doi: 10.11591/ijpeds.v11.i3.pp1398-1405.
- [2] R. Panigrahi, S. K. Mishra, S. C. Srivastava, A. K. Srivastava, and N. N. Schulz, "Grid integration of small-scale photovoltaic systems in secondary distribution network - a review," *IEEE Transactions on Industry Applications*, vol. 56, no. 3, pp. 3178–3195, May 2020, doi: 10.1109/TIA.2020.2979789.
- [3] R. Pradhan and A. Panda, "Performance evaluation of a MPPT controller with model predictive control for a photovoltaic system," *International Journal of Electronics*, vol. 107, no. 10, pp. 1543–1558, Oct. 2020, doi: 10.1080/00207217.2020.1727027.
- [4] J. Von Appen and M. Braun, "Sizing and improved grid integration of residential pv systems with heat pumps and battery storage systems," *IEEE Transactions on Energy Conversion*, vol. 34, no. 1, pp. 562–571, Mar. 2019, doi: 10.1109/TEC.2019.2892396.
- [5] R. K. Varma and E. M. Siavashi, "Enhancement of solar farm connectivity with smart PV inverter PV-STATCOM," *IEEE Transactions on Sustainable Energy*, vol. 10, no. 3, pp. 1161–1171, Jul. 2019, doi: 10.1109/TSTE.2018.2862405.
- [6] Y. Parvez and M. M. Hasan, "Exergy analysis and performance optimization of bagasse fired boiler," *IOP Conference Series: Materials Science and Engineering*, vol. 691, no. 1, p. 012089, Nov. 2019, doi: 10.1088/1757-899X/691/1/012089.
- [7] J. Khazaei, Z. Tu, and W. Liu, "Small-Signal Modeling and Analysis of Virtual Inertia-Based PV Systems," *IEEE Transactions on Energy Conversion*, vol. 35, no. 2, pp. 1129–1138, Jun. 2020, doi: 10.1109/TEC.2020.2973102.
- [8] P. K. Bhatt and S. Y. Kumar, "Impact of solar PV inverters on the power quality of smart urban distribution grid," *International Journal of Electrical Engineering & Technology (IJEET)*, vol. 8, no. 2, pp. 18–24, 2017.
- [9] L. Wang, R. Yan, and T. K. Saha, "Voltage management for large scale PV integration into weak distribution systems," *IEEE Transactions on Smart Grid*, vol. 9, no. 5, pp. 4128–4139, Sep. 2018, doi: 10.1109/TSG.2017.2651030.
- [10] K. K. M. Siu and C. N. M. Ho, "System Model and performance evaluation of single-stage buck-boost-type manitoba inverter for PV applications," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 8, no. 4, pp. 3457–3466, Dec. 2020, doi: 10.1109/JESTPE.2019.2952077.
- [11] M. Ehtesham and M. Jamil, "Control techniques for enhancing performance of PV system under dynamic conditions," *International Journal of Energy Sector Management*, vol. 15, no. 1, pp. 119–138, Jan. 2021, doi: 10.1108/IJESM-02-2020-0017.
- [12] G. A. Madrigal *et al.*, "Fuzzy logic-based maximum power point tracking solar battery charge controller with backup stand-by AC generator," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 16, no. 1, p. 136, Oct. 2019, doi: 10.11591/ijeecs.v16.i1.pp136-146.




- [13] S. A. Tadjer, A. Idir, and F. Chekired, "Comparative performance evaluation of four photovoltaic technologies in saharan climates of Algeria: ghardaïa pilot station," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 18, no. 2, p. 586, May 2020, doi: 10.11591/ijeecs.v18.i2.pp586-598.
- [14] H. Wang, M. Liserre, and F. Blaabjerg, "Toward reliable power electronics: Challenges, design tools, and opportunities," *IEEE Industrial Electronics Magazine*, vol. 7, no. 2, pp. 17–26, Jun. 2013, doi: 10.1109/MIE.2013.2252958.
- [15] Y. Yang, K. Zhou, and F. Blaabjerg, "Current harmonics from single-phase grid-connected inverters-examination and suppression," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 4, no. 1, pp. 221–233, Mar. 2016, doi: 10.1109/JESTPE.2015.2504845.
- [16] Z. Yao and L. Xiao, "Control of single-phase grid-connected inverters with nonlinear loads," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1384–1389, Apr. 2013, doi: 10.1109/TIE.2011.2174535.
- [17] R. Langella, A. Testa, J. Meyer, F. Moller, R. Stiegler, and S. Z. Djokic, "Experimental-based evaluation of PV inverter harmonic and interharmonic distortion due to different operating conditions," *IEEE Transactions on Instrumentation and Measurement*, vol. 65, no. 10, pp. 2221–2233, Oct. 2016, doi: 10.1109/TIM.2016.2554378.
- [18] A. B. Mohammed, M. A. M. Ariff, and S. N. Ramli, "Power quality improvement using dynamic voltage restorer in electrical distribution system: An overview," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 17, no. 1, pp. 86–93, Jan. 2019, doi: 10.11591/ijeecs.v17.i1.pp86-93.
- [19] A. Benali, M. Khiat, T. Allaoui, and M. Denai, "Power quality improvement and low voltage ride through capability in hybrid wind-PV farms grid-connected using dynamic voltage restorer," *IEEE Access*, vol. 6, pp. 68634–68648, 2018, doi: 10.1109/ACCESS.2018.2878493.
- [20] D. Li, K. Yang, Z. Q. Zhu, and Y. Qin, "A novel series power quality controller with reduced passive power filter," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 1, pp. 773–784, Jan. 2017, doi: 10.1109/TIE.2016.2527727.
- [21] H. Hu, Q. Shi, Z. He, J. He, and S. Gao, "Potential harmonic resonance impacts of PV inverter filters on distribution systems," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 1, pp. 151–161, Jan. 2015, doi: 10.1109/TSTE.2014.2352931.
- [22] S. Swain, P. C. Panda, and B. D. Subudhi, "Three phase shunt active power filter using a new weighted adaptive hysteresis band current controller," in *2014 International Conference on Circuits, Power and Computing Technologies, ICCPCT 2014*, Mar. 2014, pp. 781–786, doi: 10.1109/ICCPCT.2014.7054937.
- [23] R. Belaidi, A. Haddouche, and H. Guendouz, "Fuzzy logic controller based three-phase shunt active power filter for compensating harmonics and reactive power under unbalanced mains voltages," *Energy Procedia*, vol. 18, pp. 560–570, 2012, doi: 10.1016/j.egypro.2012.05.068.
- [24] S. Devassy and B. Singh, "Performance analysis of proportional resonant and ADALINE-based solar photovoltaic-integrated unified active power filter," *IET Renewable Power Generation*, vol. 11, no. 11, pp. 1382–1391, Sep. 2017, doi: 10.1049/iet-rpg.2017.0045.
- [25] A. Sangwongwanich, Y. Yang, D. Sera, H. Soltani, and F. Blaabjerg, "Analysis and modeling of interharmonics from grid-connected photovoltaic systems," *IEEE Transactions on Power Electronics*, vol. 33, no. 10, pp. 8353–8364, Oct. 2018, doi: 10.1109/TPEL.2017.2778025.
- [26] R. Panigrahi, B. Subudhi, and P. C. Panda, "Model predictive-based shunt active power filter with a new reference current estimation strategy," *IET Power Electronics*, vol. 8, no. 2, pp. 221–233, Feb. 2015, doi: 10.1049/iet-pel.2014.0276.

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