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Gravitational Search Algorithm for Power Quality Improvement of WECS with UPQC

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Abstract: In this paper, gravitational search algorithm (GSA) is used for improving the control strategy of unified power quality conditioner (UPQC). The UPQC is considered with wind energy conversion system (WECS) and grid/load to determine the dynamic behaviors. The proposed control technique alleviates the power quality (PQ) problems in the WECS. Here, the GSA approach is used to identify the ideal solutions from the available search space and the method enables the UPQC to perform under different test conditions. Initially multiple parameters are considered such as, voltage, real and reactive power and current. Amid the load variations, the proposed method will regulate the power loss, and voltage instability problem. The proposed system is tested for different PQ issues. In order to evaluate the effectiveness of the proposed method, three different cases are considered they are performance of GSA under balanced condition, under unbalanced condition, under motor speed condition. The performance of the proposed GSA based UPQC system is validated through simulations using MATLAB/Simulink and compared with existing techniques such as FA, base model and ANFIS techniques. From the comparison analysis, we can infer that the proposed control technique is very much effective in enhancing the power quality of the system than the existing techniques.

Keywords: GSA, WECS, UPQC, Series APF, Shunt APF, Grid, Load, Voltage.

1. Introduction

With the growing energy demand, the electric utilities and end users of electric power are increasingly concerned about the quality of power [1]. The expansion of renewable energy resources such as wind, solar, tidal, biomass, hydro, and co-generation is essential to meet the growing energy need [2, 3]. The need to incorporate renewable energy viz. wind energy into the power system is to minimize the environmental impact caused by the conventional plants [4 - 7]. The power quality issues have turned out to be complex at all levels of power system [8, 9]. To enhance the quality of power supplied to the distributed system the power electronic based power conditioning devices can be the effective solution. The unified power quality conditioner (UPQC) is one of the essential power electronic devices used for compensating voltage perturbations [10] and current perturbations such as reactive current and THD [11, 12]. U. Vadivu et al. [13] have proposed a combined firefly algorithm (FFA) and recurrent neural network (RNN) algorithm based UPQC and WECS to compensate the voltage sag problem. The optimal control pulses to the series and shunt APF based on the source and load side parameters are generated to improve PQ in distribution system. R. Patjoshi et al. [14] have presented a control strategy for three-phase three-wire UPQC named fixed switching methodology based on fuzzy sliding mode pulse width modulation (FSMPWM) to eliminate numerous power quality issues in the distribution network.

A new control algorithm for unified power quality conditioner is proposed by A. Panda and N. Patnaik [15]. They have introduced new synchronous reference frame (SRF) based power angle control

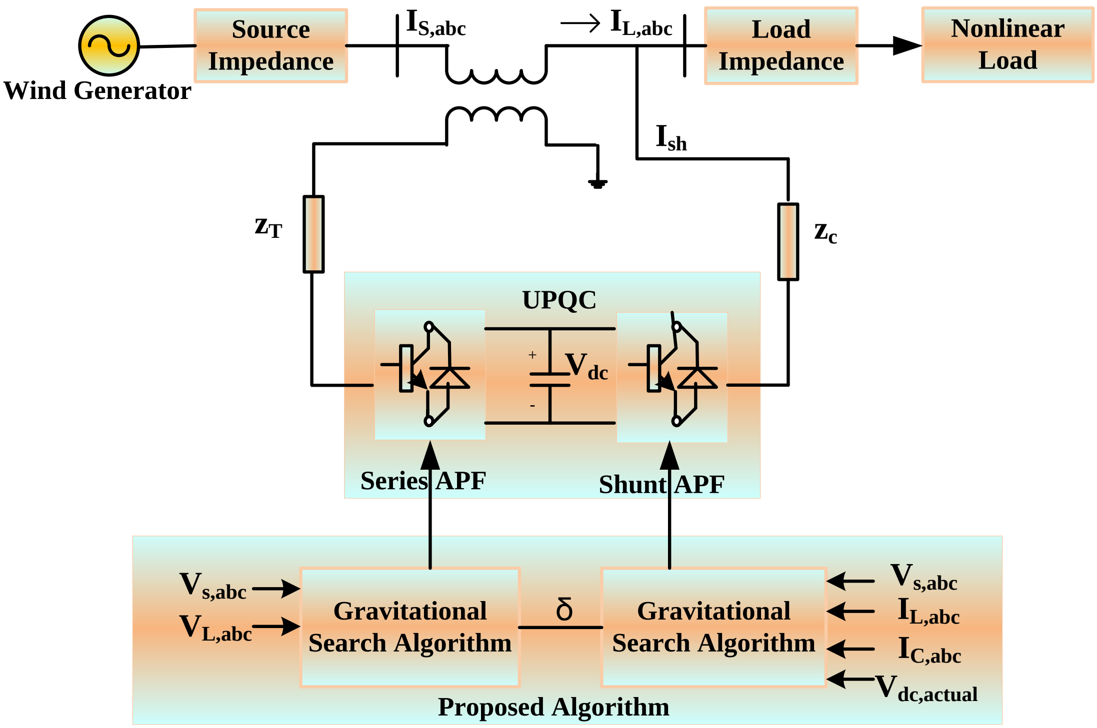


Figure. 1 Structure of WECS with UPQC and proposed controller

(PAC) method for fixed and equal reactive power sharing between series and shunt inverter independent of varieties in source voltage. W. Tareen et al. [16] has acquainted the most advanced technique to enhance the power quality of the DER and DPGS, innovative and novel developments in the field on grid connected inverters. Q. Xu et al. [17] have proposed a single-phase unified power quality conditioner (UPQC) based on the modular multilevel matrix converter (M3C) to enhance the power quality in the medium/high voltage distribution power systems. The drawbacks found in the FFA technique are search space limited by initial population. In RNN, it exhibits limitations like accepts a fixed sized vector as input. Although the above mentioned techniques are utilized for enhancement of PQ and complexity in algorithms still exist. To overcome these challenges, optimal PQ enhancement using advanced technology is required. In related works, few control technique are presented to solve the PQ issues in the WECS; the above-mentioned limitations have motivated to do this research work. In this paper, gravitational search algorithm (GSA) is used for improving the control strategy of unified power quality conditioner (UPQC).The UPQC is considered with wind energy conversion system (WECS) and grid/load to determine the dynamic behaviors. The proposed control technique alleviates the power quality (PQ) problems in the WECS. The definite depiction of the proposed method is illustrated in the following section 2. Section 3 depicts the results and discussion. Section 4 concludes the paper.

2. Proposed model for WECS with UPQC

The proposed strategy of Gravitational Search Algorithm (GSA) enhances the power quality of the system. The Fig. 1 delineates the WECS with UPQC and the control methodology. Here, the unbalance and harmonic distortion of the UPQC system implies the non-ideal condition. The permanent magnet synchronous generator (PMSG) operated by a wind turbine, rotor side converter, dc to dc transitional circuit and a grid side converter [18] are the components of WECS. The instantaneous power angle δ is evolved for presenting the sharing characteristics of reactive power among the series and shunt inverter.

2.1 Control strategies of the UPQC system

The UPQC comprises of two main controllers: one is series active power filter connected in series with the load and the other is shunt active power filter connected to the power system.

1) Series Active Power Filter: Fig. 2 illustrates the proposed gravitational search algorithm-based control signal generator for series APF. The transformation angle acquired from modified PLL is

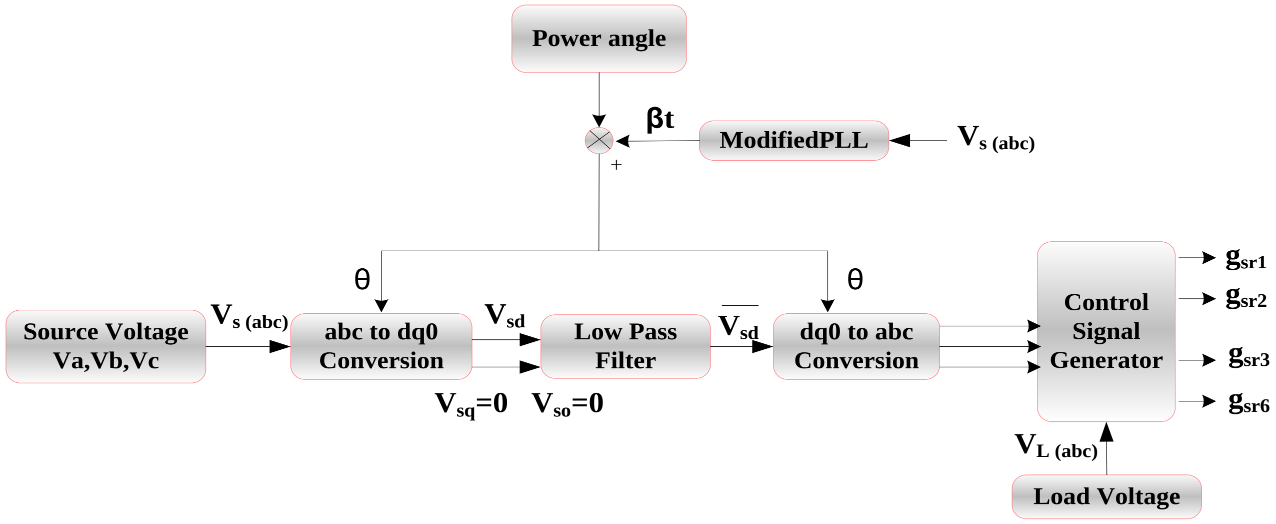


Figure. 2 Control Structure of series active power filter

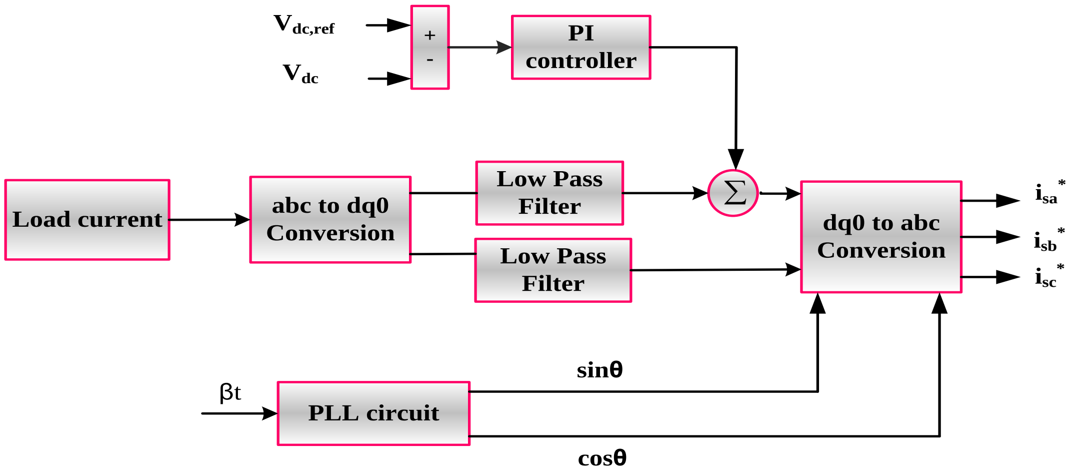


Figure. 3 Control structure of shunt active power filter

represented as βt. The PI controller is utilized for getting the optimal gain parameters, in modified PLL and the proposed technique is evolved. By then, the unbalanced condition in the source voltage and the arrangements of q axis and zero axis voltages are set to low to disregard harmonics. Here, V_{sd}, V_{sq} refers stator voltages. g_{sr1}, g_{sr2}, g_{sr3}, g_{sr6} are the control signal generators, $V_{L\ (abc)}$ specifies load voltage, $V_{s\ (abc)}$ specifies source voltage, θ as phase angle difference between V_s and V_L without a parallel compensator.

2) Shunt Active Power Filter: Fig. 3 depicts the control structure of shunt active power filter with UPQC. Here, the regulation of the dc link voltage is expert by their currents. For assessing the reference compensation current, the dc link voltages are enhanced. By then, for both proposed controlling technique in series and shunt APG, the adjusted PLL is utilized. The tuned low pass filter is utilized to isolate the normal section. Here, V_{dc} refers dc link voltage, $V_{dc,ref}$ indicates the reference value of dc link voltage, β indicates phase advance angle of injected voltage with respect to V_s, reference currents in three-phase system as i_{sa}^*, i_{sb}^*, i_{sc}^*.

2.2 Proposed gravitational search algorithm for generation of control pulses

Gravitational Search Algorithm is a new meta-heuristic optimization algorithm developed by E. Rashedi et al. [19]. This algorithm is motivated by the Newton's famous law of gravity and the law of motion. Due to gravity, the objects are attracted to each other and also towards the objects with the heavier masses [20]; this force causes a global movement of all the objects.

Procedure step of gravitational search algorithm

Step 1: Initialization of the agents

In this step, we need to initialize the input parameters such as source side and load side parameters such voltage and current, and the position of the j^{th} agent,

$$X_j = \left(x_j^l, \dots, x_j^m, \dots x_j^s\right) for\ j = 1, \dots, n \tag{1}$$

Where, x_j^m is the position of the j^{th} mass in m^{th} dimension and s is the space dimension.

Step 2: Fitness Evaluation

The fitness functions of all agents are done in order to generate the optimal control pulses. The fitness function for best and worst are computed and is described as follows,

$$best(t) = min\, fit_i(t) for\ i\epsilon\{1, \dots n\} \tag{2}$$

$$worst(t) = max\, fit_i(t) for\ i\epsilon\{1, \dots n\} \tag{3}$$

Where, $fit_i(t)$ represents the fitness of i^{th} agent at iteration t, $best(t)$ represents minimum (best) fitness of all agents and $worst(t)$ represents maximum (worst) fitness of all agents.

Step 3: Gravitational Constant Computation

The gravitational constant $G(t)$ is computed using the t iteration by the ensuing Eq. (4).

$$G(t) = G_0\ exp(-\alpha \frac{t}{T}) \tag{4}$$

The gravitational constant G_0 is initialized and which is reduced with time to control the accuracy for searching.

Where, $G(t)$ is the value of the gravitational constant at time t, G_0 is the value of the gravitational constant at the first cosmic quantum-interval of time t, α is the constant, T shows total iteration number and t is the current generation.

Step 4: Update the Inertial Masses

The inertial masses are updated by the subsequent iteration.

$$mg_i(t) = \frac{fit_i - worst(t)}{best(t) - worst(t)} \tag{5}$$

The mass of the j^{th} agent is given as

$$Mg_j(t) = \frac{mg_j(t)}{\sum_{j=1}^{n} mg_j(t)} \tag{6}$$

Step 5: Total Force Calculation

The total force acting on the j^{th} agent at iteration t is evaluated as follows.

$$F_j^d(t) = \sum_{i\in kbest\ i\neq j}^{n} rand_i\, F_{ji}^d(t) \tag{7}$$

Where, $rand_i$ is a random number between interval [0, 1] and the set of first K agents is k-best with the best fitness value and biggest mass. According to the gravitational theory the force acting on the j^{th} mass $M_j(t)$ from the i^{th} mass $M_i(t)$ is described in the below equation.

$$F_{ji}^d(t) = G(t) \frac{M_j(t) \times M_i(t)}{R_{ji}(t) + \in} \left(x_i^d(t) - x_j^d(t)\right) \tag{8}$$

Step 6: Calculation of Acceleration and Velocity

The acceleration $a_j^d(t)$ at iteration t and velocity of the j^{th} agent at next iteration $(t+1)$ in d^{th} dimension is updated through the law of gravity and law of motion as succeeding equation.

Where, $\in$ is the constant and the Euclidian distance between j^{th} and i^{th} agents are defined as $R_{ji}(t)$.

$$a_j^d(t) = \frac{F_i^d(t)}{Mg_j(t)} \tag{9}$$

Where, $Mg_j(t)$ is the inertial mass of j^{th} agent.

$$v_j^d(t+1) = rand_j \times v_j^d(t) + a_j^d(t) \tag{10}$$

Step 7: Update the agent's position

Then the next positions of j^{th} agents in d^{th} dimension are updated as follows.

$$x_j^d(t+1) = x_j^d(t) + v_j^d(t+1) \tag{11}$$

Step 8: Return Best Solution

The steps from 2 to 7 are repeated until the iteration reaches their maximum limit. At the final iteration, the best solutions of algorithm are computed as a global fitness function of the problem and at specified dimensions the position of the corresponding agent acts as the global solution to that problem. The flowchart of the Gravitational Search Algorithm is depicted in Fig. 4.

3. Results and discussions

In this segment, the proposed algorithm is utilized for analyzing the PQ problems. Here the performance of the proposed GSA is validated in the MATLAB/Simulink platform. The UPQC control signal calculation is based on the variation in the

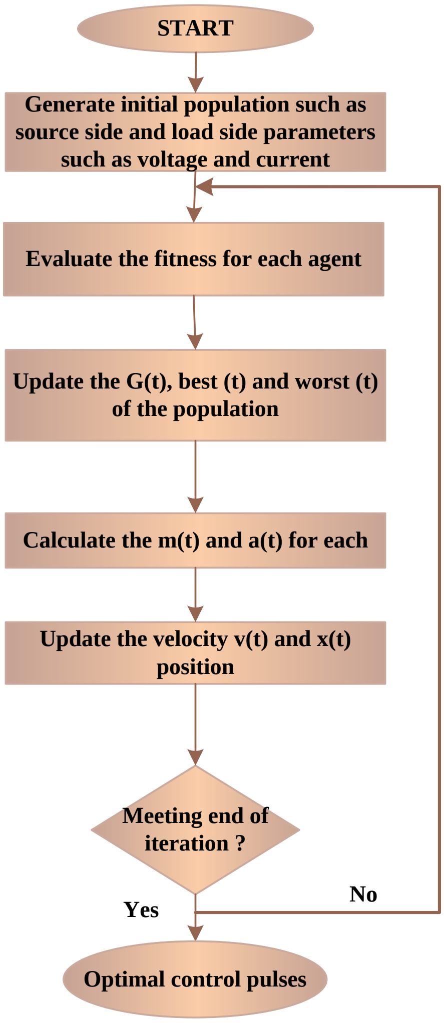


Figure. 4 Flow chart diagram of GSA

source side as well as load side parameters such as voltage and current, which is done by utilizing the proposed strategy. In order to show the effectiveness of the proposed strategy, the proposed strategy is compared with various existing techniques such as FA [13], base model and ANFIS [13].

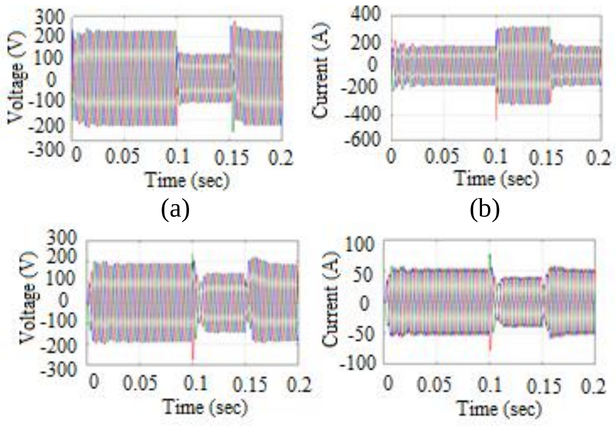
3.1 Experimental analysis

The proposed system is tested for different PQ issues. In order to evaluate the effectiveness of the proposed method, three different cases are considered and the results are described below. The parameter table for PMSG is tabulated in Table 1 [21].

- **Case A**: Performance of GSA under balanced condition
- **Case B**:Performance of GSA under unbalanced condition
- **Case C**:Performance of GSA under motor speed condition

Table 1. Parameters of PMSG

Parameter of PMSG	Value
Rated power	2 MW
Rated mechanical speed	2.57 rad/sec
Stator resistance	0.008Ω
Stator d-axis and q-axis inductance	0.0003H
Permanent magnet flux	3.86wb
Pole pairs	60



(a) (b)

(c) (d)

Figure. 5 Performance: (a) source voltage, (b) source current, (c) load voltage, and (d) load current under balanced condition

Case A: Performance of GSA under balanced condition

Under the balanced condition, the control pulses of the series and shunt APF are divided by proposed method on the basis of the source and load side parameters. With the UPQC, the non-linear load is analyzed along with the new control strategy. The proposed system determines the perturbations considering both the load and source side parameters. The performance of source voltage and source current under balanced condition can be analyzed in Figs. 5 (a) and (b).

As observed from figure, the amplitude of source voltage and source current the graph is diminished to about 25% from its nominal value at t=0.1 to 0.15 sec under balanced condition. The Figs. 5 (c) and (d) demonstrate the performance of control signals, for example, load current and load voltage. The load current is fluctuated at typical condition when time t=0.1 to 0.15 sec. Also for the load voltage at the point when the disturbance happens, the typical signals oscillates between t=0.1 to 0.15 sec under balanced condition.

Figs. 6 (a) and (b) illustrate the performance of rectifier current and voltage. Here, the current signal of the rectifier is 255 V and the voltage is at 55A. The real (P) and reactive (Q) of load at balanced condition utilizing the proposed technique is analyzed in Figs. 6 (c) and (d). After certain period, in the real load analysis, under balanced condition if the disturbance happens, an exceptional variation in the graph which can be seen at *t*= 0.1 to 0.15 sec.

As seen from figure, the injected voltage is begun at time t=0 sec and oscillation is happened at *t*= 0.1 to 0.15 sec. Fig. 7 (a) shows the performance of injected voltage under balanced condition. When the disturbance happens, the injected voltage varies at to= 0.1 to 0.15 sec. Fig. 7 (b) shows the motor speed, 7 (c) shows the response of torque 7 (d) shows the response of stator voltage. The motor speed is always changed at 120 as appeared in Fig. 7 (b). In Fig. 7 (c) the torque performance is analyzed at *t*=0and at *t*=0.1 and the effect of disturbance also happens. In Fig. 7 (d) the stator voltage performance is analyzed at t=0.1 to 0.15 sec, the disturbances occur.

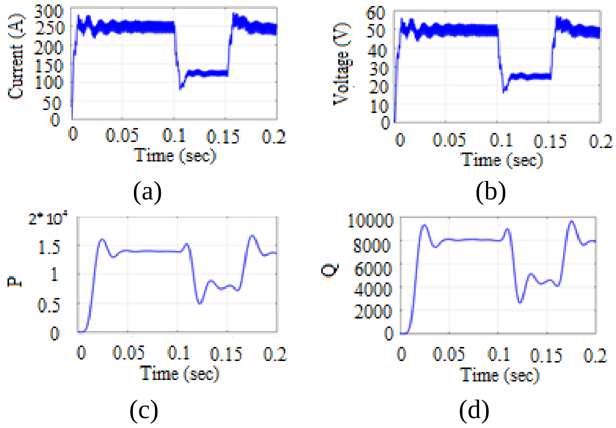


Figure. 6 Performance: (a) rectifier current, (b) rectifier voltage, (c) load P, and (d) load Q using proposed technique

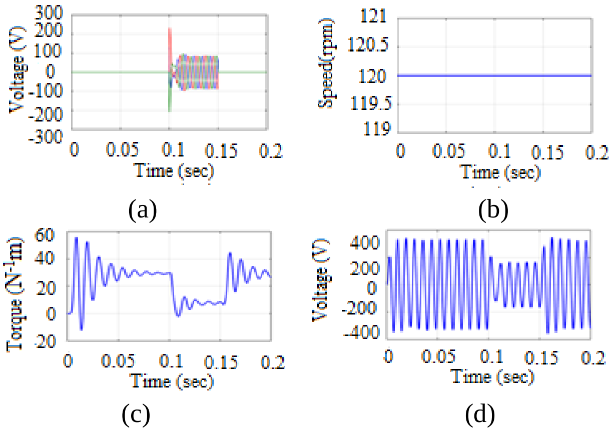


Figure. 7 Analysis: (a) injected voltage, (b) motor speed, (c) torque, and (d) stator voltage using proposed under balanced condition

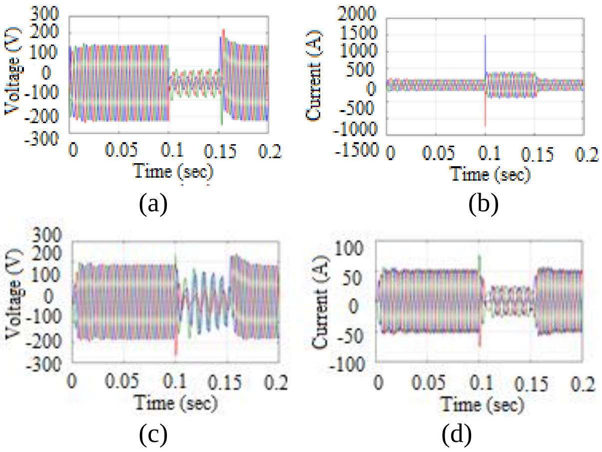


Figure. 8 Performance: (a) source voltage, (b) source current, (c) load voltage, and (d) load current under unbalanced condition

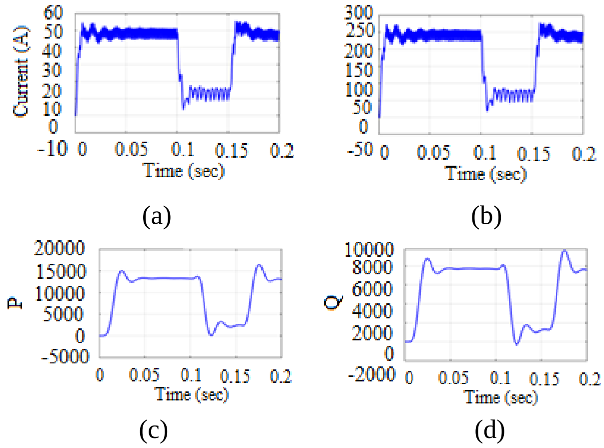


Figure. 9 Performance: (a) rectifier current, (b) rectifier voltage, (c) load P, and (d) load Q using proposed technique

Case B: Performance of GSA under unbalance condition

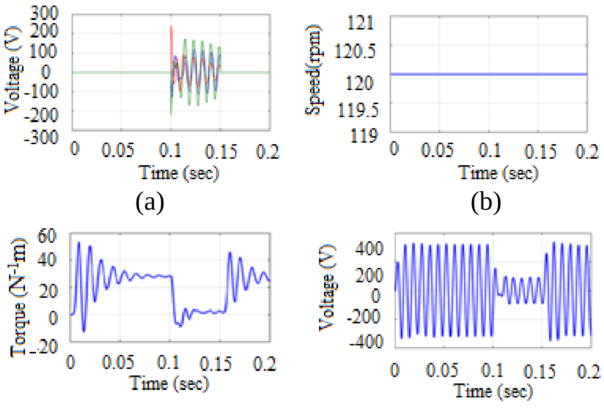
The unbalanced condition is explored by utilizing the different strategies in case B. By utilizing the proposed method, the source voltage, source current, load voltage, load current, and real/reactive load separately are investigated. The various framework exhibitions are analyzed and simulated. The performance of simulation results of source voltage and source current analysis under unbalance conditions is represented in Figs. 8 (a) and (b). Based on the performance of the proposed method with unbalanced condition is slightly better than the other methods. When the fault happens, the typical signal oscillates between *t*=0.1 to 0.15 sec as depicted in Figs. 8 (c) and (d). Figs. 9 (a) and (b) represent the rectifier current and voltage, in which the waveforms are analyzed and the oscillations are shown at *t*=0.1 to 0.15 sec. The Load active and reactive waveforms are shown in Figs. 9 (c) and (d). As seen from the figure, the proposed control algorithm takes less cycles to process the change in the load-active and reactive power. The waveform of injected voltage in unbalanced condition is represented in Fig. 10 (a). Fig. 10 (b) demonstrates the performance evaluation of the motor speed.

Fig. 10 (c) demonstrates the performance evaluation of the response of torque. Fig. 10 (d) demonstrates the performance evaluation of the response of stator voltage. The motor speed is always changed at 120 as appeared in Fig. 10 (b). In Fig. 10 (c) the torque performance is analyzed at *t*=0 and at *t*=0.1 and the effect of disturbance also happens. In Fig. 10 (d) the stator voltage performance is analyzed at *t*=0.1 to 0.15 sec, the disturbances occur.

Case C: Performance of GSA under motor speed condition

The Performance of source voltage and source current are analyzed under motor speed condition as shown in Figs. 11 (a) and (b), while the simulation time is at *t*= 0.1 to 0.2 sec. The Figs. 11(c) and (d) demonstrate the performance of control signals such as load current and load voltage. In motor speed condition using the proposed technique, the disturbances in the rectifier current and rectifier voltage are made and variation appears at time *t*= 0.1 to 0.2 sec which is appeared in Figs. 12 (a) and (b). In Figs. 12 (c) and (d), the load P and Q varies under motor speed condition at t=0.1 to 0.2 sec, when the disturbance occurs. From these results, it can be noticed that the settling time, rise time is also analyzed based on the load P and Q.

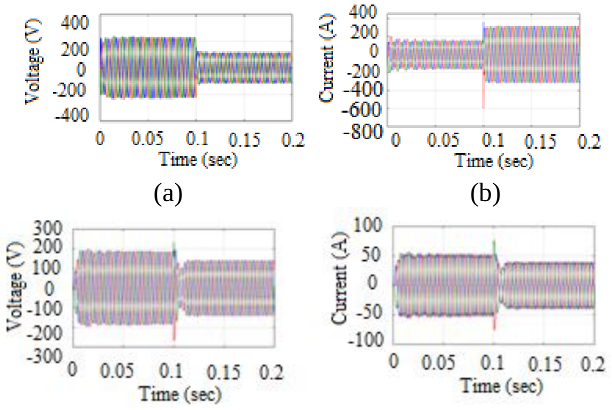
In Fig. 13 (a) the injected voltage is seen at t= 0 to 0.1 sec, at that point the disturbances are seen at time t= 0.1 sec. Here, the proposed GSA technique has been tested for output distortions. The motor speed condition is shown in Fig. 13 (b). In Fig. 13 (c) the torque performance is analyzed, the system begins at t=0 and the unsettling influence is observed at t=0.1s. In Fig. 13 (d) the experimental analysis of the stator voltage under motor speed condition is plotted. The disturbances in the stator voltage are made and variation appears at to=0.1 to 0.2 sec. Thus, from the comparison analysis of the various parameters, the variations of proposed control method is compared with the other existing techniques such as base model and firefly algorithm for the minimization of PQ issues, and improvement of the system operation. On the overall analysis, the performance of source voltage and current, load voltage and current, rectifier current and voltage, load real and reactive power, injected voltage, motor speed, torque and stator voltage are analyzed. Based on the overall analysis, the proposed method gives the optimal solution because of the good searching ability and it makes the system more optimal than the other existing techniques such as FA, base model and ANFIS.



(a) (b)

(c) (d)

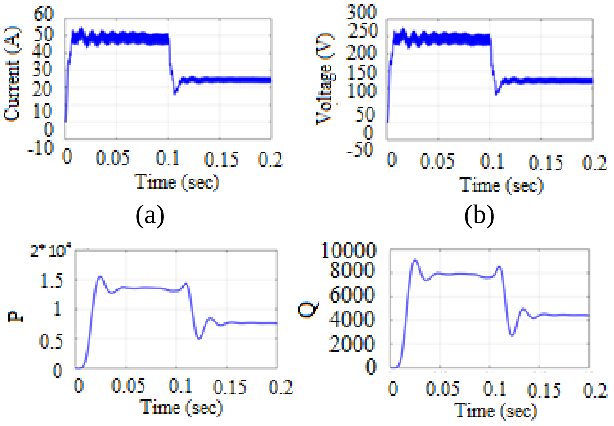
Figure. 10 Experimental analysis: (a) injected voltage, (b) motor speed, (c) torque, and (d) stator voltage using proposed under unbalanced condition



(a) (b)

(c) (d)

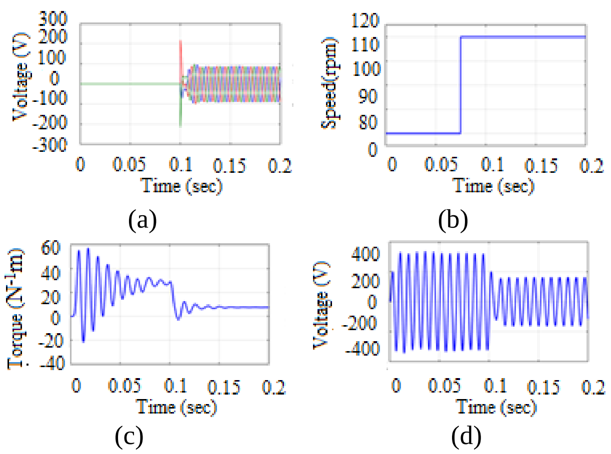
Figure. 11 Performance: (a) source voltage, (b) source current, (c) load voltage, and (d) load current in test case C



(a) (b)

(c) (d)

Figure. 12 Performance: (a) rectifier current, (b) rectifier voltage, (c) load P, and (d) load Q using proposed technique



(a) (b) (c) (d)

Figure. 13 Experimental analysis: (a) injected voltage, (b) motor speed, (c) torque, and (d) stator voltage in test case C

4. Conclusion

In this paper, the PQ improvement with the help of UPQC has been proposed with GSA technique. The performance of proposed method is implemented in MATLAB/Simulink platform. Utilizing the UPQC device, the balanced, unbalanced and the speed conditions are evaluated for different conditions. The performance of source voltage and current, load voltage and current, rectifier current and voltage, load real and reactive power, injected voltage, motor speed, torque and stator voltage are analyzed. The main objective of the proposed control method is analyzed and the unbalanced voltage problems are compensated. Here, the nonlinear load is considered as the induction motor. The proposed control strategies effectiveness is verified through a comparative analysis with different existing techniques such as FA and base model respectively. From the comparison analysis, we can infer that the proposed control technique is very much effective in enhancing the power quality of the system than the other techniques. The future scope is the control techniques can be enhanced to design different control schemes. The proposed scheme can be used with battery-based system even in the absence of wind energy. Voltage stability of power systems with a large share of distributed energy resources need to be further studied along with optimization of location of FACTS devices. In the proposed system to achieve better performance, artificial intelligence techniques may also be incorporated.

References

[1] M. Hossain and M. Ali, "Future Research Directions for the Wind Turbine Generator System", *Renewable and Sustainable Energy Reviews*, Vol. 49, No. 9, pp. 481-489, 2015.

[2] S. Mohod and M. Aware, "A STATCOM-Control Scheme for Grid Connected Wind Energy System for Power Quality Improvement", *IEEE Systems Journal*, Vol. 4, No. 3, pp. 346-352, 2010.

[3] T. Ayodele and A. Ogunjuyigbe, "Mitigation of Wind Power Intermittency: Storage Technology Approach", *Renewable and Sustainable Energy Reviews*, Vol. 44, No. 4, pp. 447-456, 2015.

[4] L. Suganthi, S. Iniyan, and A. Samuel, "Applications of Fuzzy Logic in Renewable Energy Systems – A Review", *Renewable and Sustainable Energy Reviews*, Vol. 48, No. 8, pp. 585-607, 2015.

[5] M. Amin and O. Mohammed, "Development of High-Performance Grid-Connected Wind Energy Conversion System for Optimum Utilization of Variable Speed Wind Turbines", *IEEE Transactions on Sustainable Energy*, Vol. 2, No. 3, pp. 235-245, 2011.

[6] M. Singh, V. Khadkikar, A. Chandra, and R. Varma, "Grid Interconnection of Renewable Energy Sources at the Distribution Level with Power-Quality Improvement Features", *IEEE Transactions on Power Delivery*, Vol. 26, No. 1, pp. 307-315, 2011.

[7] S. González and M. Valla, "UPQC Implemented with Cascade Asymmetric Multilevel Converters", *Electric Power Systems Research*, Vol. 124, No. 7, pp. 144-151, 2015.

[8] Y. Bouzelata, E. Kurt, R. Chenni, and N. Altın, "Design and Simulation of A Unified Power Quality Conditioner Fed by Solar Energy", *International Journal of Hydrogen Energy*, Vol. 40, No. 44, pp. 15267-15277, 2015.

[9] A. Merabet, M. Islam, R. Beguenane, and A. Trzynadlowski, "Multivariable Control Algorithm for Laboratory Experiments in Wind Energy Conversion", *Renewable Energy*, Vol. 83, No. 11, pp. 162-170, 2015.

[10] P. Li, Y. Li, and Z. Yin, "Realization of UPQC H∞ Coordinated Control in Microgrid", *International Journal of Electrical Power & Energy Systems*, Vol. 65, No. 2, pp. 443-452, 2015.

[11] B. Jain, S. Jain, and R. Nema, "Control strategies of Grid Interfaced Wind Energy Conversion System: An Overview", *Renewable and Sustainable Energy Reviews*, Vol. 47, No. 7, pp. 983-996, 2015.

[12] H. Jadhav and R. Roy, "Stochastic Optimal Power Flow Incorporating Offshore Wind Farm and Electric Vehicles", *International Journal of Electrical Power & Energy Systems*, Vol. 69, No. 7, pp. 173-187, 2015.

[13] U. Vadivu and B. Keshavan, "Power quality enhancement of UPQC connected WECS using FFA with RNN", In: *Proc. of IEEE International Conf. on Environment and Electrical Engineering and IEEE Industrial and Commercial Power Systems*, pp. 1-6, 2017.

[14] R. Patjoshi, V. Kolluru, and K. Mahapatra, "Power Quality Enhancement Using Fuzzy Sliding Mode Based Pulse Width Modulation Control Strategy for Unified Power Quality Conditioner", *International Journal of Electrical Power & Energy Systems*, Vol. 84, No. 1, pp. 153-167, 2017.

[15] A. Panda and N. Patnaik, "Management Of Reactive Power Sharing & Power Quality Improvement with SRF-PAC based UPQC Under Unbalanced Source Voltage Condition", *International Journal of Electrical Power & Energy Systems*, Vol. 84, No. 1, pp. 182-194, 2017.

[16] W. Tareen, S. Mekhilef, M. Seyedmahmoudian and B. Horan, "Active Power Filter (APF) for Mitigation of Power Quality Issues in Grid Integration of Wind and Photovoltaic Energy Conversion System", *Renewable and Sustainable Energy Reviews*, Vol. 70, No. 4, pp. 635-655, 2017.

[17] Q. Xu, F. Ma, A. Luo, Z. He, and H. Xiao, "Analysis and Control of M3C-Based UPQC for Power Quality Improvement in Medium/High-Voltage Power Grid", *IEEE Transactions on Power Electronics*, Vol. 31, No. 12, pp. 8182-8194, 2016.

[18] G. Adamidis, G. Tsengenes, and K. Kelesidis, "Three Phase Grid Connected Photovoltaic System with Active and Reactive Power Control Using “Instantaneous Reactive Power Theory”, *Renewable Energy and Power Quality Journal*, Vol. 1, No. 8, pp. 1086-1091, 2010.

[19] E. Rashedi, H. Nezamabadi-pour, and S. Saryazdi, "GSA: A Gravitational Search Algorithm", *Information Sciences*, Vol. 179, No. 13, pp. 2232-2248, 2009.

[20] S. Duman, U. Güvenç, Y. Sönmez, and N. Yörükeren, "Optimal Power Flow Using Gravitational Search Algorithm", *Energy Conversion and Management*, Vol. 59, No. 7, pp. 86-95, 2012.

[21] Y. Errami, M. Ouassaid, and M. Maaroufi, "Control of a PMSG based Wind Energy Generation System for Power Maximization and Grid Fault Conditions", *Energy Procedia*, Vol. 42, No. 1, pp. 220-229, 2013.