



# Adaptive technique for PQ analysis in renewable sources with grid integrated SSFC

S. Mani Kuchibhatla<sup>1</sup> · D. Padmavathi<sup>2</sup> · R. Srinivasa Rao<sup>3</sup>

Received: 7 April 2018 / Accepted: 24 March 2019 / Published online: 4 April 2019  
© Springer-Verlag GmbH Germany, part of Springer Nature 2019

## Abstract

In power quality (PQ) problems, the flexible AC transmission system (FACTS) devices have been developed the real power and reducing the PQ issues of the power system. Here the PQ analysis in photovoltaic (PV), wind turbine (WT) system with grid integrated static switched filter compensator (SSFC) is controlled by adaptive technique. The adaptive technique works with the combined process of Cuttle fish algorithm (CFA) and recurrent neural network (RNN) algorithm. The proposed adaptive technique is controlling the irregular switching process of the shunt capacitor banks of a tuned arm filter in SSFC device. The novelty of the proposed technique is improved for energy efficiency and demand management in grid utilization process. Here a power injection model of SSFC is considered to control the real power flow control in terms of grid utilization. The switching process is controlled by balancing control signal generated with the help of pulse width modulation (PWM) process. To modulate the PWM is used by two regulators, which is based on a tri-loop real error managed combined weighted adjusted proportional integral derivative controller. The proposed SSFC system is designed and implemented in MATLAB/Simulink platforms and the performance is validated with some existing devices such as unified power flow controller and SSFC devices.

**Keywords** PQ · PV · Micro grid · WT · FACTS · SSFC · PID controller · CFA · RNN algorithm

## 1 Introduction

Generally, the microgrid is a small independent system, which can be structured by connecting several distributed energy sources such as solar, wind, fuel cells, biomass etc. (Kabalcı and Kabalcı 2007). The solar and wind power generation system with energy storage source is stabilized the demand power under load variations also prevent the sudden variation and increase the reliability of the consumers (Derrouazin et al. 2017). The obstacle of the transmission network is a growing flow of renewable energy, the increasing demand for electrical power and the aging of networks (Kirthika and Balamurugan 2016). The interconnection of

the DGs is to the grid is based on the power converters, which stabilizes the output power. The power converters are used compensate for the optimal operation and control the parameters. Though, this interface forms PQ issues in an output power (Gayatri et al. 2018). There are some PQ issues are as voltage harmonics, voltage swells, voltage sags, voltage unbalance, reactive power compensation (RPC), current harmonics, current unbalance and circulation of neutral currents, impulse transients and interruptions (Sharaf and Abdelsalam 2012).

Recently, the main goals of the electric power systems are improving the quality of power and reduce the PQ issues (Modesto et al. 2015). The PQ issues develop important concerns by growing applications of dissimilar and electronically switched devices in distribution systems and industries (Teke et al. 2011). After that, develop PQ in power systems by dissimilar compensators such as passive filters and static compensators (Esfahani et al. 2015). The emerging technologies like FACTS and custom power devices (CPDs) can support electric companies to a pact with overhead problems (Qader 2015). The CPD involve distribution static compensator (DSTATCOM) (Kamel et al. 2015). Unified power

✉ S. Mani Kuchibhatla  
smani03710@gmail.com

<sup>1</sup> Jawaharlal Nehru Technological University, Kakinada, India

<sup>2</sup> Department of Electrical and Electronics Engineering, Sridevi Womens Engineering College, Hyderabad, India

<sup>3</sup> Department of Electrical and Electronics Engineering, J.N.T University College of Engineering, Kakinada, India

quality conditioner (UPQC) and dynamic voltage restorer (DVR) (Gonzaleza et al. 2014) are used for recompensing the PQ issues by controlling the power parameters (Kannan and Rengarajan 2012). Then FACTS device is a family of power electronic products composed with the static synchronous compensator (STATCOM), UPFC (Zhang 2003) and static synchronous series compensator (SSSC).

In these devices has the high controlling ability also have the capability for improving performances of the power system like voltage and power in transmission lines (Mehrjerdi and Ghorbani 2017). For improving the performance of the power system the FACTS devices are utilized the VSCs, which contains the power semiconductor devices like gate turn off switches and isolated gate bipolar transistors (Wang and Truong 2013; El Moursi et al. 2008). Also, it offers a powerful mechanism that controls the reactive power and voltage in power systems (Farahani 2012). The controller for dynamic, active power flow control is designed in power networks named as SSSC (Vinkovic and Mihalic 2008). Moreover, the SSSC is operated for measuring the power of the transmission line (Benabid et al. 2012). Based on the requirements the SSSC is reduced harmonic in both capacitive and inductive load performances (Ullah et al. 2017). Here, the dynamic power flow control model of SSFC with adaptive technique is proposed for improving the performance of the proposed system. The adaptive technique is the combination of CFA and RNN for controlling the switching process of the converters. The description of the proposed system and the proposed controlling technique is presented in Sect. 3. Then the performance evaluation based on the simulated results is presented in Sect. 4. Finally, the presented paper is concluded with the performance of the proposed system. Before that, the literature about the active power controlling model of FACTS in Sect. 2, this is presented as follows.

## 2 Recent research works: a brief review

There are many research works are presented based on renewable sources with FACTS devices. Some recent literary works are illustrated as follows.

The WECS, PV energy conversion system (PVECS) based dynamic model and the PVECS control and the power electronics devices have described by Chaurasia et al. (2017). The control strategy for grid-integrated hybrid wind/PV distributed generation system has to control the voltage and frequency in the point of common coupling (PCC) by utilizing the firefly based controller.

A fuel cell (FC), battery, solar panel and wind turbine based energy management algorithm (EMA) for a smart home have presented by Arabul et al. (2017). The EMA controller was utilized with a fuzzy logic controller. In an

off-grid smart home the FC as the main energy source that provided by alternative energy sources (AES) which gives more quality, economic and eco-friendly energy.

The double fed induction generators (DFIGs), squirrel cage induction generators (SCIGs) wind farm and a combined wind farm (CWF) based three-phase grid fault has presented by Rashad et al. (2017). For the meantime, the CWF was comprised of an equal number of DFIGs and SCIGs, which were stimulated with SSSC controller to shift the active and reactive power flow.

A multi-functional single-stage grid-tied solar photovoltaic (SPV) system with STATCOM capabilities using a cascaded three phases seven level voltage source converter (VSC) have accessible by Hussain et al. (2017). The proposed system performs in three modes, the first mode was only active power, the second model was both active and reactive powers and the mode 3 was only reactive power was delivered to the grid.

Nandi et al. (2018) have presented moth–flame optimization (MFO) algorithm for UPFC–RFB-based load frequency stabilization of a realistic power system with various nonlinearities. A nature-inspired MFO algorithm was employed as an optimization tool in the design of proportional–integral–derivative gains and the tunable parameters of UPFC and RFBs. The substantial point of discussion was the guaranteed convergence mobility as the moths in algorithm update their positions with respect to the flames which represent the most promising solutions.

Kaushal and Basa (2018) have proposed fuzzy inference system for determination of power quality monitoring index of an AC microgrid. The main objective of paper was to propose a decision-making methodology to assess the power quality of a single-phase AC microgrid using MATLAB–Simulink software. The power quality-related electrical parameters are considered as voltage, frequency, power factor and total harmonic distortion. To quantify the fuzziness in random variation of power quality, a power quality monitoring index (PQMI) was proposed using 256 rule-based fuzzy inference systems for a single-phase microgrid model.

Arya et al. (2019) have presented the gravitational search algorithm (GSA) for the analysis of Distribution system (DS) with accurate placing and sizing of distributed static synchronous compensator (D-STATCOM) for power loss reduction, minimum voltage profile index, improvement in voltage profile and annual energy saving for distribution network operator.

The Thyristor switched capacitors (TSC) integrate TCR based SVC system was utilized for compensating load over generation or absorption of reactive power or matching nonlinear load has proposed by Mukhopadhyay et al. (2017). In an arc furnace application the TCR is used to control the flicker and the light load condition the TCR is restrained

overvoltage occurrences of a network. However, the linear current drawn by TCR has caused in the need for additional harmonic current filters to be used through such systems in order to occur PQ.

An efficient operation of micro grid (MG) integrated wind energy systems are utilized on distributed FACTS based green plug switched filter capacitor (GP-SFC) filter have presented by Gandomann et al. (2017). The variable speed wind turbine system was used as a dynamic multi-loop error driven controller for correcting the pulse switching pattern. Moreover, the GP-SFC filter can stimulate the consumption of wind energy system in load changes and temporary fault conditions.

As the above survey, some consistent models of this device have been reachable in the literature. The coordination of energy produced system presents specialized difficulties for which voltage regulation and PQ issues are to be considered. A few energy produced systems have different PQ attributes. The PQ is essential for high power user which is seriously influenced by the distribution and transmission networks. These services are provided in addition to dynamic power generation, responsive absorption and infusion to accomplish voltage control, regulation and adjustment to meet load variations. The main PQ issues on grid integrated power produced systems are a variation of power, flicker and harmonics. Therefore, the PQ issues depend upon an imbalance power at the generator under sudden variations and electric load groups.

The custom power devices (CPDs) and FACTS have been created for reducing the particular PQ issues. The CPDs are synchronous static compensator (STATCOM), dynamic voltage restorer (DVR), UPFC, solid-state fault current limiter

and solid-state transmission switch. The UPFC is used for controlling the power flow, DVR is utilized for voltage sag compensation a series compensator and STATCOM is utilized for voltage sag and reactive power compensation as a shunt compensator of the power system. Dynamic control and enhanced switching of the semiconductor devices have attained at an innovative way for mitigation of PQ issues. The importance of another category of unified series-shunt compensator (USSC) can relieve a more extensive scope of PQ issues. Several FACTS devices developed on switched filter compensator, which is utilized the guideline of USSC. There are some uncommon strategies prescribed to determine this issue in literature however they all are inefficient. The above-cited problems have assorted to do this study work. Consequently, the adaptive technique based SSFC control is described here. The proposed technique along with the proposed system is explained as a followed section.

### 3 The methodology of the proposed system

In this section discussed the structure of the proposed system with the adaptive technique for reducing the PQ issues. The proposed system consists of PV, wind power generation system and SSFC integrated grid power system. The PV and wind power generated systems are helped with converters and transformers for power transmission of the network. The structure of the proposed system along with the adaptive technique is illustrated in Fig. 1. The adaptive technique is the combination of CFA and RNN algorithm for stabilizing the performance of the SSFC by controlling the switching process.

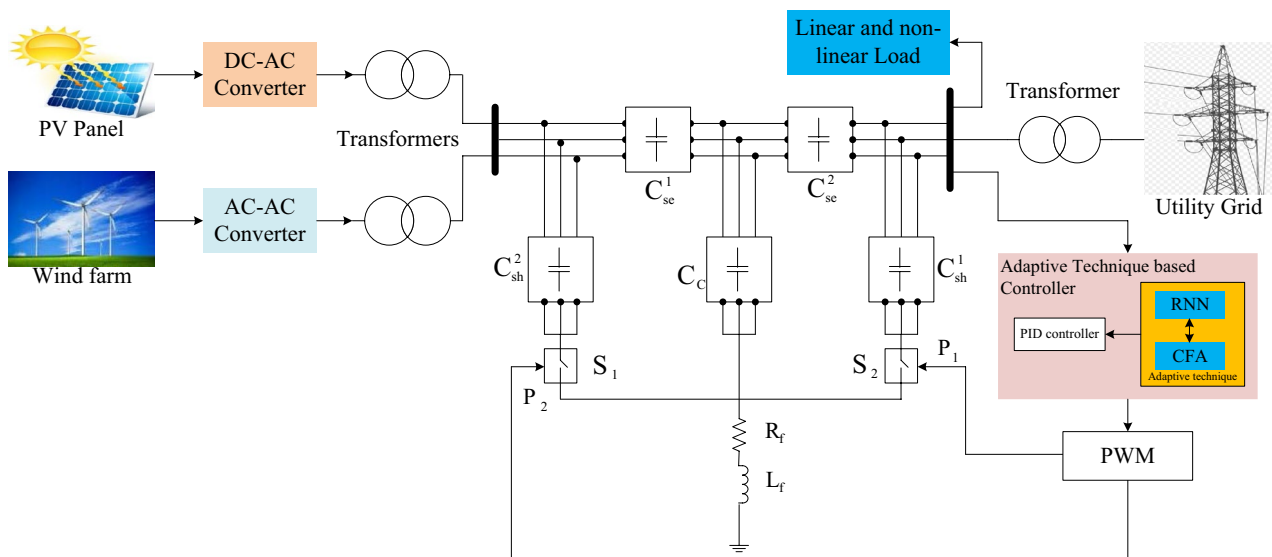


Fig. 1 The control structure of a renewable power generation system with SSFC integrated grid

Initially, the power generation of PV and wind are measured and given to the utility grid using the transformer. The grid signals are measured and analyzed with the generated power and required power also analyzed for PQ issues. If the signal is affected with the PQ disturbance the SSFC device is connected to the transmission line and controls the PQ issues. After that, the grid power is measured and compared with the required power. Then the compensated power is improved by utilizing the adaptive technique in SSFC. The adaptive technique is utilized to modify the switching process of the capacitor banks of the SSFC. The estimation process of the transmitted power, grid power and the inverter voltage are evaluated. The power generation systems configuration detailed explanation is presented in the followed section.

### 3.1 The PV and wind power generation system

In this section described the PV modules, which are coupled with the common dc bus through a dc–dc converter. The solar module is connected to a diode in parallel and it acts as the current source. In this PV array, the strings are designed essentially linked the solar modules (Hua et al. 2018). The maximum power depends on the output voltage that is generated under solar irradiance by using the maximum power point tracking (MPPT). Then the generated maximum power is transmitted by the boost converter. The PV array generated power depends on the cell temperature and solar irradiation that is described as Eq. (1),

$$P_{pv} = P_{pv}^{rated} \times \frac{G}{1000} \times \eta_{mppt}. \tag{1}$$

Here, the solar irradiation is denoted as  $G$  at the PV surface ( $w/m^2$ ),  $P_{pv}^{rated}$  is the rated power for  $1000 w/m^2$  and the module efficiency is described as  $\eta_{mppt}$ . Initially, the solar irradiance is  $250 w/m^2$  and then increase slowly to  $1000 w/m^2$  also temperature keeps constant  $25^\circ C$ . Then the wind power generation system is explained as follows. The simple wind turbine model is utilized for the generating power from the wind speed, air density and windmill area

(Ghorbani et al. 2018). The generated power from a wind turbine is described as Eq. (2),

$$P_{wt} = 0.5\rho ACV_{wt}^3. \tag{2}$$

At the moment, the air density is denoted as  $\rho$ , the windmill area perpendicular to the wind ( $m^2$ ), the wind turbine power coefficient is  $C$  and  $V$  denotes the wind velocity (m/s) at the height of the turbine hub, which is given as Eq. (3),

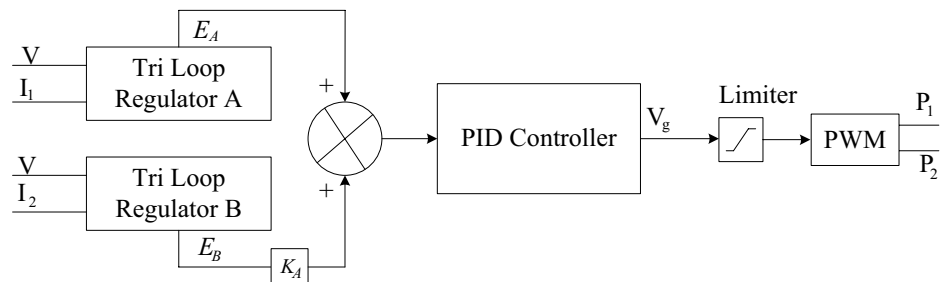
$$\frac{V_1}{V_2} = \left(\frac{H_1}{H_2}\right)^\alpha. \tag{3}$$

By consuming  $V_1$  as the wind velocity at a reference height denoted by  $H_1$  and  $\alpha$  is the Hellman coefficient. Normally, the generated power is transmitted to the grid with the help of transformers and converters. If the power fluctuation is affected by the transmitted power then the SSFC is used for compensating the output voltage for reducing the PQ issues. The controlling design of the SSFC is explained as a followed subsection.

### 3.2 The controller design for SSFC

In this subsection presented the design of the controller in the SSFC, which is illustrated in Fig. 2. The SSFC system has two shunt or parallel capacitors  $C_{sh}^1$  and  $C_{sh}^2$  banks and two series capacitor  $C_{se}^1$  and  $C_{se}^2$  banks both are combined with each other. The parallel capacitors are utilized for reactive power compensation also develops the regulation of the distribution feeder. The series capacitors are used as a dynamic voltage booster and inrush current limiting device. The capacitor element  $C_c$  is connected series for a tuned arm filter  $R_f$  and  $L_f$ . The controlling process is reducing the reactive power losses and stabilizes the power flow of the feeders. The enhanced switching process for the parallel capacitor is processed by the proposed adaptive controlling technique. The two parallel capacitor bank switches are controlled by a control pulse signals  $P_1$  and  $P_2$  generated by PWM that are produced through the dynamic tri-loop error driven modified PI controller. In this process two tri-loop error regulators are utilized for reducing the harmonics,

Fig. 2 The standard controller design of the SSFC



developing the power factor and regulate the bus voltages of the SSFC (Sharaf and Abdelsalam 2013).

The two tri-loop error driven dynamic controllers are adequate for the switched filter compensator such as tri-loop regulator A and tri-loop regulator B. In regulator A is utilized for regulating the tri-loop error measured from the voltage and current waveform to improve the power factor and to supply an established voltage at every AC buses. Then the regulator B is utilized to control the harmonics and ripples from the difference of the measured voltage and current.

In the proposed system, the SSFC is used to improve the power factor, stabilize the buses voltage and reduce the harmonics in the system. The harmonics reduction is achieved with the utilization of the PID controller. The multi loop error values are minimized by optimal tuning of the PID controller which is attained through the use of the adaptive technique. The control technique also defined as a traditional dynamic control. The output of PID  $V_c$  is the modulating control signal to the PWM switching block. The global error ( $e(t)$ ) is the summation of a multi-loop individual errors including voltage stability and current limiting errors.

The voltage stability error is designed as Eq. (4),

$$e_V^2 = V_2^{ref} - V_2 \left( \frac{1}{1 + ST_1} \right). \quad (4)$$

The current limiting error is described as Eq. (5),

$$e_I^2 = I_2 \left( \frac{1}{1 + ST_1} \right) \left( 1 - \frac{1}{1 + ST_2} \right). \quad (5)$$

The global error is evaluated as Eq. (6),

$$e(t) = e_{V+}^2 + e_I^2. \quad (6)$$

Addition of the two error signal is given to the PID controller for regulating the control signal to the PWM for controlling the switching sequence of the shunt capacitor bank switches. In this controlling structure have two ideal switches  $S_1$  and  $S_2$  are used also the corresponding switching pulses  $P_1$  and  $P_2$  that are generated by utilizing the dynamic tri-loop error driven PID controller. The switching losses of the switches are based on the switching frequency of switches based on the control objects. The PWM controlling pulses of the SSFC is developed by the variable topology of the switches. In this process the switch  $S_1$  is in ON state and  $S_2$  is in OFF state, the compensation process of the AC distribution system is performed by the resistor and inductor and the corresponding shunt and series capacitors based on the requirements (Gamaa et al. 2016). When the switch  $S_1$  is OFF state and  $S_2$  is ON state, the inductor and the resistors will interconnect to the circuit as a tuned arm filter. The error controlling process is performed as the input to the self-tuned PID controller. The signal of the PWM form in the time domain for the PID controller has given in Eq. (7),

$$V_c = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{d(e(t))}{dt}. \quad (7)$$

Generally, the PID controllers are used in industries because they are uncertain in nature and reveal powerful performance over a massive range of operating conditions. These kinds of controllers are the best dynamic collections in the absence of whole information of the development. The Proportional (P), Integral (I) and Derivative (D) are the three main parameters elaborate in PID controller. The proportional part is responsible for succeeding the anticipated reference parameters, whereas the integral and derivative portion account for the growth of past errors and the rate of change of error in the method correspondingly. The PID controller gives the voltage signal ( $V_c$ ) to the PWM for generating control pulse signal to the switches. The PID controller parameters are optimized by using the proposed adaptive technique. The detailed explanation of the proposed technique is presented in the following section.

### 3.3 The PID controller parameters optimization using adaptive technique

In this section described the optimization parameters and the procedure of the proposed adaptive technique. The adaptive technique is the composite of the CFA and RNN algorithm. The CFA is utilized for controlling the SSFC switching sequence of the switches and RNN is enhancing the update function of the CFA for improving the performance of the proposed system. The CFA is a meta-heuristic optimization algorithm, which is established on the mechanism of color changing behavior of cuttlefish. This is utilized to find the optimal solution in numerical optimization problems. The optimization procedure of the CFA algorithm is presented as follows.

#### 3.3.1 Mechanisms of skin color change in Cuttlefish algorithm

The algorithm was developed based on the techniques used by the cuttlefish to change its skin color for camouflage. The two main process used in CFA is reflection and visibility to generate a new solution. The reflection process mimics or simulates how the cells of cuttlefish reflect the light. The proposed algorithm mimics the work of the three cell layers that are used by cuttlefish to change its skin colors. Reflection process represents the mechanism used by cuttlefish to reflect incoming light and it can be any case of the six cases. While visibility is representing the matching pattern clarity that the cuttlefish try to simulate the patterns appear in its environment. We assumed that the final pattern is the global optimum solution, while visibility is the difference between

the best solution and the current solution (Eesa et al. 2015). The formulation of finding the new solution ( $S_{new}$ ) using reflection and visibility is described in (8),

$$S_{new} = Reflection + Visibility. \quad (8)$$

The CFA starts with random solutions for initializing the population. Then the six cases are applied until a stop condition will meet. The steps of the CFA algorithm are summarized as follow,

**3.3.1.1 Initialization** Initialize the population with random solutions, calculate and keep the best solution and the average value of the best solution's points. First, the population  $P$ (cells) of  $N$  initial solutions  $P = cells = \{p_1, p_2, \dots, p_n\}$  is spread over  $d$ -dimensional problem space at random positions ( $p$ ) using (9),

$$P[i].p[j] = rand(0, 1) * (U_L - L_L) + L_L; \quad i = 1, 2, \dots, N; j = 1, 2, \dots, d. \quad (9)$$

Here  $U_L$  and  $L_L$  are the upper and the lower limits in the problem domain and  $rand$  is a function used to produce a random number between (0, 1). Each individual  $p_i$  of the population represents a single cell and it is associated with two values, fitness and a vector of  $d$ -dimension continuous values. After that, the best solution will be kept in  $Best$ , and the average of the  $Best$  points are calculated and stored in  $AV_{Best}$ . Then the population (cells) is divided into four groups of cells. Each group will work independently sharing only the best solution, two of them (group 1 and 4) are work as a local search, while group 2 and 3 are work as a global search.

**3.3.1.2 Group 1, simulation of case 1 and 2** In this group, use the interaction operator between chromatophores and iridophores cells in case 1 and 2, to produce a new solution based on the reflection and the visibility of pattern (global search). Reflected color (light) is produced due to the interaction between chromatophores and iridophores cells, each chromatophore cell will contract or relax its muscles to stretch or shrink its saccule. While iridophores cells will reflect the light that is coming from chromatophores cells. The reflected light, my penetrates the chromatophores cells or not. The stretch and shrink process in chromatophores cells and the reflected light from iridophores cells and visibility of the pattern used by cuttlefish to match its background are used to find a new solution, which is described in (10) and (11), respectively:

$$Reflection_j = R * G_i[i] \cdot P[j], \quad (10)$$

$$Visibility = V * (BestP[j] - G_i[i] \cdot P[j]). \quad (11)$$

Here,  $G_1$  represents a group of chromatophores cells used to simulates case (1 and 2). The  $i$ th cell of the group  $G_1$  denoted as  $i$ .  $P[j]$  represent the  $j$ th point of  $i$ th the cell. The

best solution points are represented as  $Best \cdot P$ . The reflection degree  $R$  is used to find the stretch range of the saccule when the muscles of the cell are in contract or relax. The visibility degree  $V$  is the final view of the pattern. The value of  $R$  and  $V$  are calculated as Eqs. (12) and (13),

$$R = rand(0, 1) * (r_1 - r_2) + r_2, \quad (12)$$

$$V = rand(0, 1) * (v_1 - v_2) + v_2. \quad (13)$$

Here,  $r_1$  and  $r_2$  are two constant values used to find the stretch interval of the chromatophores cells. While  $v_1$  and  $v_2$  are two constant values used to find the interval of the visibility's degree of the final view of the pattern. Sometime the value of  $R$  or value of  $V$  is just set to 1, otherwise, it will be calculated. In this group, only the value of  $V$  is set to 1 and  $R$  will be calculated. Shortly, the search space of the problem is too big, thus these operations reduce the search space between two specific values such as in the example between (-10, 20). This group work as a global search uses the value of each point to finding the new area around the best solution with a specific interval.

**3.3.1.3 Group 2, simulation of case 3 and 4** In this group, use iridophores cells operators in case 3 and 4 to calculate new solutions based on the reflected light coming from the best solution and the visibility of the matching pattern (local search). The iridophores cells are light reflecting cells will reflect incoming light from the outside (environment), and the reflected color is a specific color (Eesa et al. 2014). Iridophores cells are assisting in concealment or used to conceal organs. We assumed that the concealed organs are represented by the best solution. So the formulation of finding the visibility is remaining as it, while the formulation of finding the reflection is rewritten as Eq. (14),

$$Reflection_j = R * Best \cdot P[j]. \quad (14)$$

For this group the value of  $R$  is set to 1, while the value of  $V$  will be calculated. This group woks as a local search uses the difference between the best solution and the current solution to produce an interval around the best solution as a new search area.

**3.3.1.4 Group 3, simulation of case 5** In this group use leucophores cells operator in case 5 to produce a new solution by reflecting light from the area around the best solution and visibility of the pattern (local search). Leucophores cells are work as a mirror. In this way, the cells will reflect the predominant wavelength of light in the environment. In the white light, they will reflect the white, in the brown light, they will reflect brown and etc. In this case 5 the light is coming through chromatophores cells with specific color. The reflected light is very similar to the light that coming

from the chromatophores cells. In order to cover the similarity between the incoming color and the reflected color, we assumed that the incoming color is the best solution (Best), and the reflected color could be any value around the Best. The interval that is used around the Best is produced by visibility. The reflection and the visibility are modified as Eqs. (15) and (16),

$$Reflection_j = R * Best \cdot P[j], \tag{15}$$

$$Visibility_j = V * (Best \cdot P[j] - AV_{Best}). \tag{16}$$

where  $AV_{Best}$  is the average value of the  $BestpointsP$ . The value  $R$  is set to 1, while the value of  $V$  is calculated. Also, this group works as a local search, but this time uses the difference between the best solution points and the average value of  $Bestpoints$  to produce a small area around the best solution.

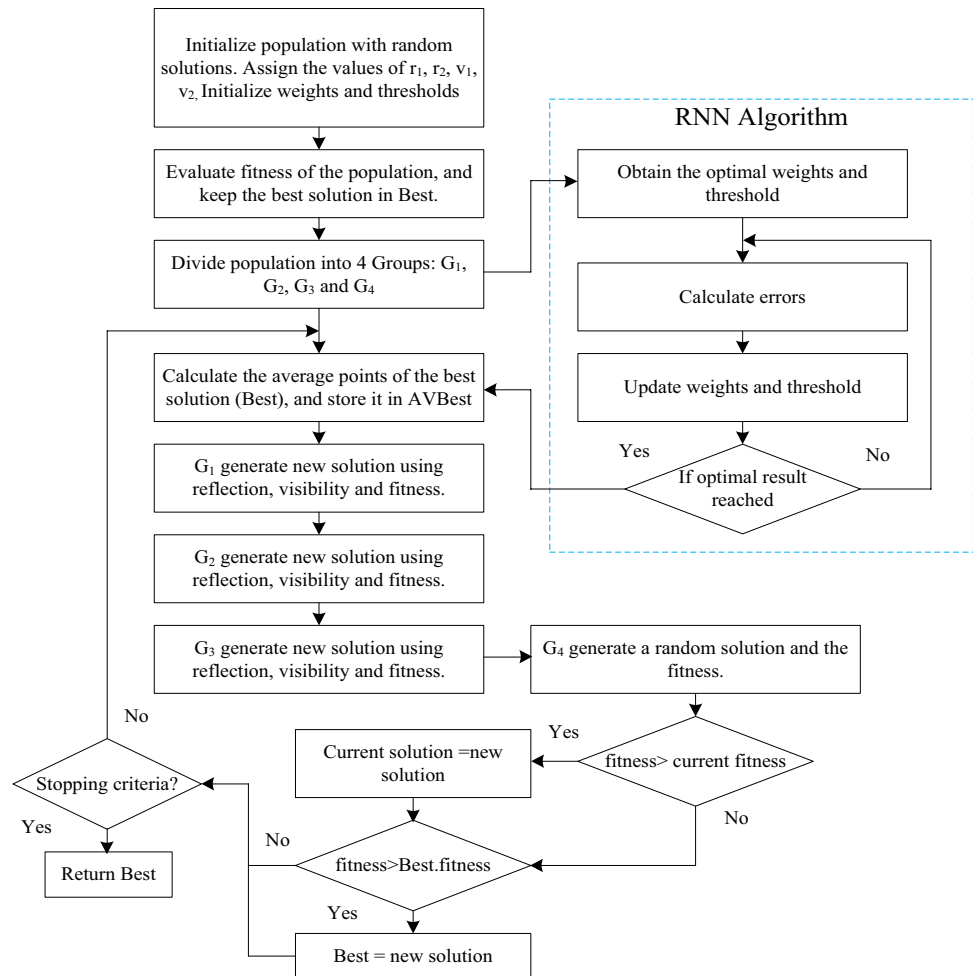
**3.3.1.5 Group 4, simulation of case 6** In this group 4 use leucophores cells operator in case 6 for random solution by

reflecting incoming light (global search). In this case, the leucophores cells will just reflect the incoming light from the environment. This operator allows the cuttlefish to blend itself into its environment. As a simulation, one can assume that any incoming color from the environment will be reflected as it and can be represented by any random solution. Thus this case 6 works as initialization use to find the new solution. Then the update function is enhanced by the RNN algorithm for improving the performance of the proposed CFA. The proposed hybrid algorithm flow diagram is presented in Fig. 3, which describes the CFA and RNN algorithm adequate procedure.

**3.3.2 Improving the searching behavior of CFA using RNN**

A simple RNN has activation feedback which has a short-term memory. A state layer is updated not only with the external input of the network but also with activation from the previous forward propagation. The feedback is modified by a set of weights to enable regular adaptation through learning. The RNN contains two phases and three layers, such as, the training phase and testing phase and input layer,

Fig. 3 The flow diagram of a proposed adaptive technique



hidden layer and output layer, here hidden layer consists of hidden and context layer, which is ‘n’ neurons are used in the hidden and context layer. There is a one-step time delay in the feedback path so that previous outputs of the hidden layer, also called the states of the network, are used to calculate new output values (Fairbank et al. 2014). The topology is similar to that of a feed-forward network, except that the outputs of the hidden layer are used as the feedback signals. The RNN has two inputs namely, error voltage ( $e$ ) and change of error voltage ( $\Delta e$ ). The output of RNN is a control signal ( $I_{out}$ ), which is generated for regulating the load reference current. The RNN output is given to the inverter current controller. Here, the input layers to hidden layer weights are specified as  $(w_{11}, w_{12}, \dots, w_{1n})$  and  $(w_{21}, w_{22}, \dots, w_{2n})$ . The arbitrary weights of the recurrent layer and the output layer neuron are generated in the specified interval  $[w_{min}, w_{max}]$ . For every neuron of the input layer weight is allocated with the unity value. The RNN is trained by using backpropagation through time delay (BPTT) algorithm with Bayesian regulation. The RNN process is based on the forward and backward pass. The procedure of Bayesian regulation BPTT algorithm is given as below.

**3.3.2.1 Procedure of BPTT algorithm with Bayesian regulation** *Step 1:* Initialize the inputs to the input layer and assign their weights. The inputs of the network is error volt-

**Table 1** Implementation parameters of the proposed technique

Parameters	Values
Dimension of the population	20
Number of cells	2
Number of iterations	20
Upper limit	10
Lower limit	0

age ( $e$ ) and change in error voltage ( $\Delta e$ ) are calculated from Eq. (17),

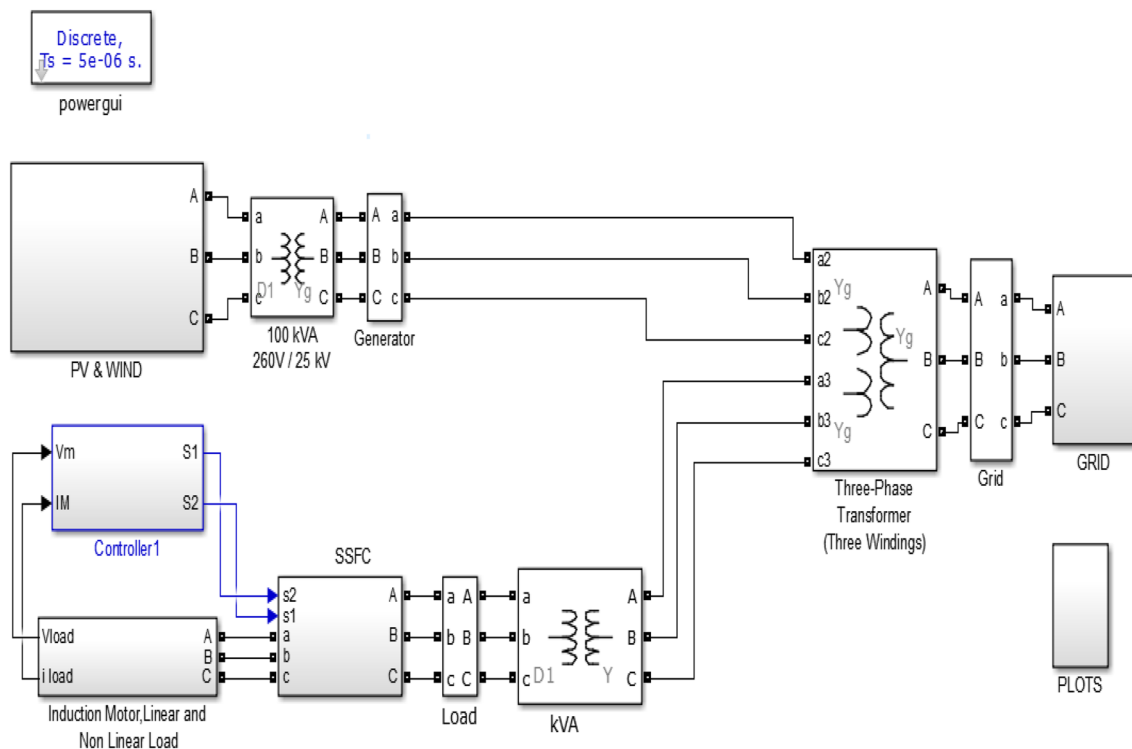
$$\left. \begin{aligned} e(t) &= V_{dc} - V_{dc}^{ref} \\ \Delta e &= e(t) - e(t-1) \end{aligned} \right\} \quad (17)$$

*Step 2:* In general, a RNN can be expressed with the following Eqs. (18) and (19),

$$x_i(t) = \sum_j y_j(t)w_{ij}(t), \quad (18)$$

$$y_i(t) = f_i(x_i(t)), \quad (19)$$

where  $y_i$  and  $w_{ij}$  specifies the activation state of neuron  $i$  at a time  $t$  and optimize weights value. The activation function  $f_i$  depends on the network inputs and context layer inputs.



**Fig. 4** The proposed simulation model of the SSFC utilized power generation and distribution system



*Step 3:* The hidden node activation function is passed through the sigmoid function to determine the decision vector is given as Eq. (20),

$$f_i = \frac{1}{1 + e^{(-x_i)}} \tag{20}$$

Where,  $i = 1, 2$  and the RNN output is  $Y^{act} = W_{2i}f_i$  for a single output system output weight matrix.

*Step 4:* In the forward process of back propagation, the output of each neuron is calculated using the function (21) and (22),

$$y_i(t) = f_i(x_i(t), C_i(t)), \tag{21}$$

$$x_i(t) = \sum_{j \in H} y_j(t)w_{ij} + \sum_{j \in I} x_j(t)w_{ij} + \sum_{j \in C} y_j(t - \tau_{ij})w_{ij}, \tag{22}$$

where  $f, H, I$  and  $C$  are denotes the activation function of a neuron, hidden layer values, input neurons values, the values of the neuron which store in information about the previous network stage. Then  $x_j$  is  $j$ th input neuron and  $\tau_{ij}$  is an integer

value indicating the displacement in recurrent connection through the times.

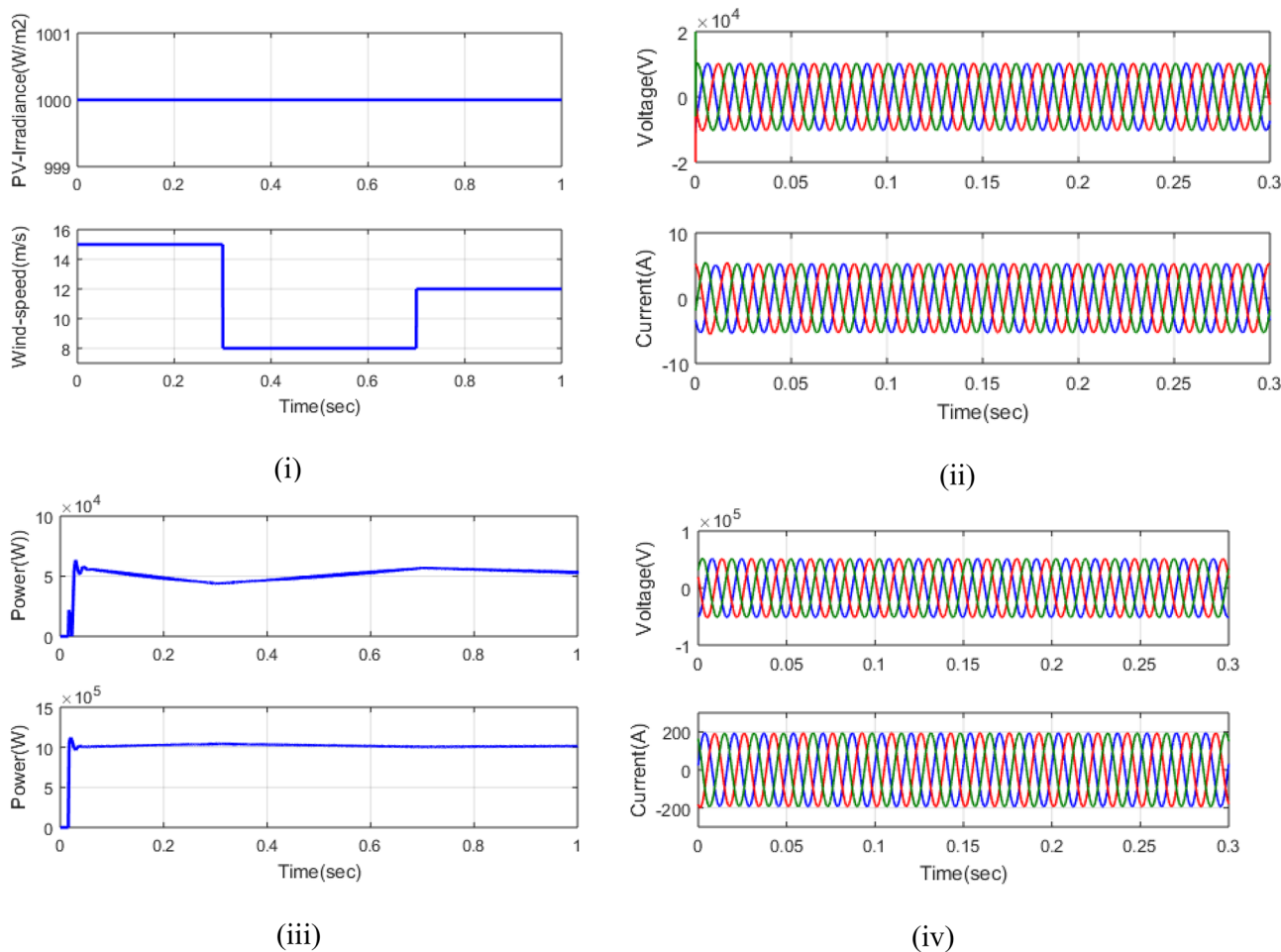
*Step 5:* The back propagation error is calculated from the Eq. (23),

$$E_m = Y^{tar} - Y^{act}. \tag{23}$$

The error can be minimized using the Bayesian Regularization approach.

*Step 6:* In this Bayesian Regulation technique, the objective function is modified by combining the mean sum of squared network errors and weights and makes a better working network by selecting the exact combination (Su and Lu 2017). These are the processes involved in the Bayesian Regularization technique, which is a function with network training and based on Levenberg–Marquardt optimization, the weight and bias values are updated in this function (24),

$$E_d = \frac{1}{N} \sum_{i=1}^N ((E_m)^2). \tag{24}$$



**Fig. 5** The response of (i) input condition, (ii) generated voltage and current, (iii) PV and wind power and (iv) SSFC voltage and current in condition 1

*Step 7:* For updating the weights, this equation is expanded in the Eq. (25),

$$B_r = \beta E_d + \alpha E_w. \quad (25)$$

Here the sum of squares of the network weights is  $E_w$ . Then  $\alpha$  and  $\beta$  are the parameters to be optimized in the Bayesian framework. Until BP error gets reduced to the least value, otherwise the process is repeated. The well-trained networks are obtained from the output of the neural network process. The current control law is generated from this network. Finally, the RNN is utilized for the CFA performances improvement and the effectiveness of the proposed technique is evaluated by Matlab/Simulink platform and the results are presented in the following section.

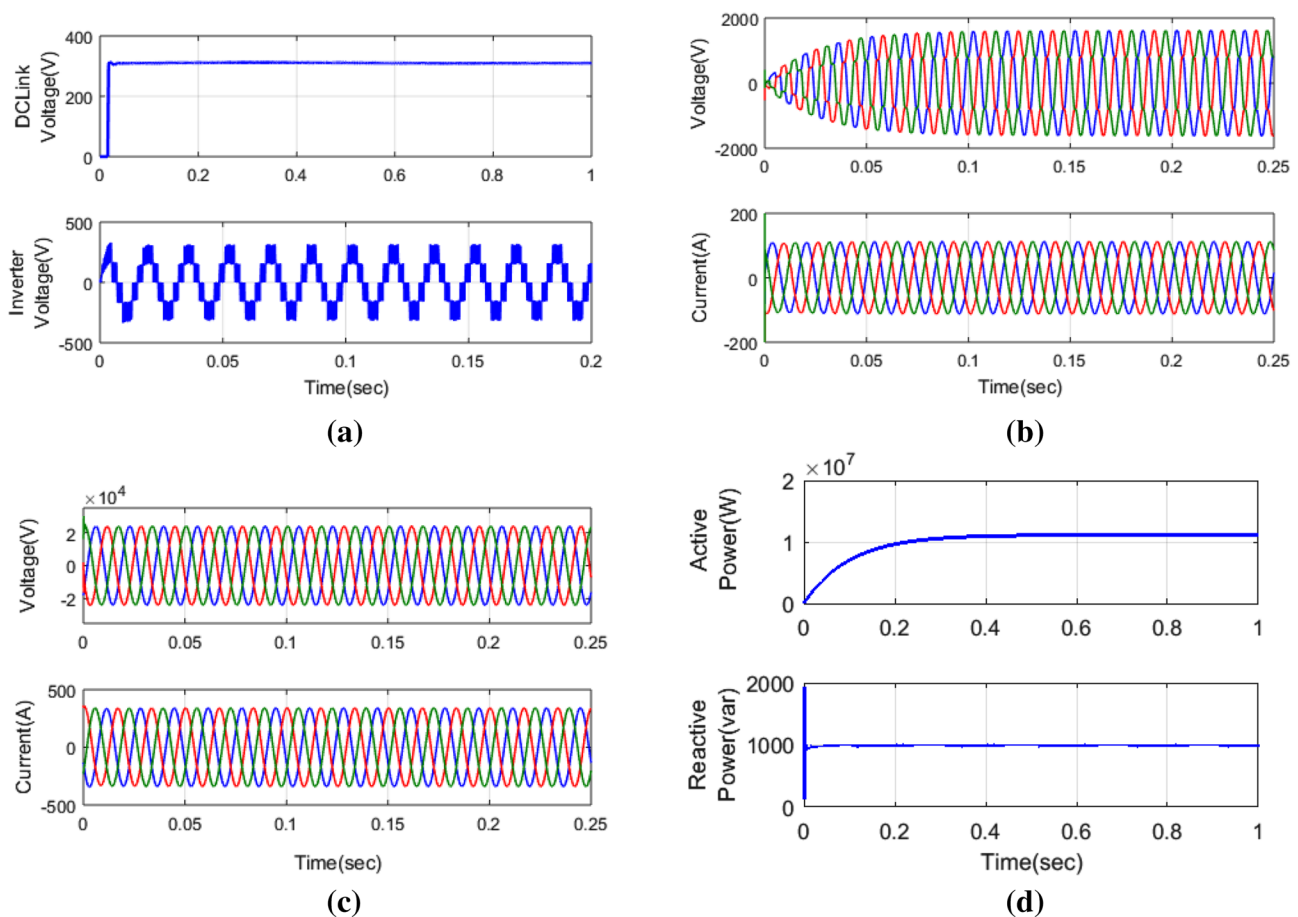
## 4 Results and discussion

The output response of the proposed system based on the simulation results is presented in this results and discussions section. The proposed system contains the PV, WECS

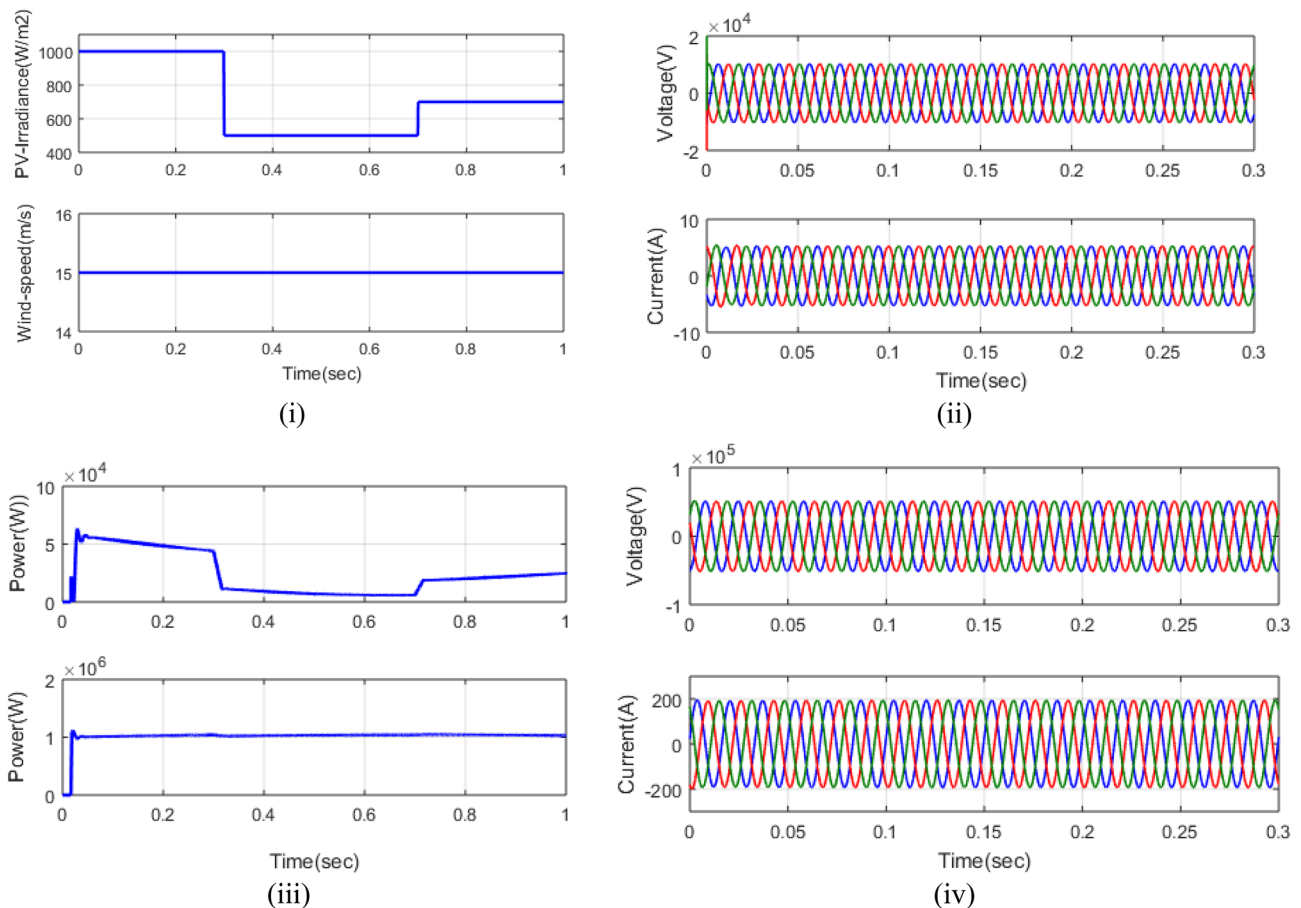
and the adaptive technique based SSFC for transmitting the regulated quality power to the linear and non-linear load, induction motor also utility grid. The proposed system is implemented in Intel(R) Core(TM) i5 processor, 4 GB RAM and MATLAB/Simulink 7.10.0 (R2015a) platform. The proposed system simulation model is exposed in Fig. 4, which is utilized to control the PQ disturbances.

The parameters of the proposed technique are calculated while implementation and presented in Table 1. Initially, the PV and wind generation system has generated the power and converted into an AC signal using the converters and transmitted to the utility grid through the transformers. Before that, the linear and non-linear load and the induction motors are connected for evaluating the effectiveness of the proposed system. Based on the analysis the grid or load power is measured and evaluated with the required power. If the power varies, the adaptive technique controlled SSFC device is compensating the adequate grid power.

To evaluate the performance of the proposed system is based on the two conditions, which is the variation of the generation section. If the generating power is varied the



**Fig. 6** The condition 1 performance analysis for **a** DC-link and inverter voltage, **b** load voltage and current, **c** grid voltage and current and **d** active and reactive power



**Fig. 7** The condition 2 performance of (i) input condition, (ii) generated voltage and current, (iii) PV and wind power and (iv) SSFC voltage and current

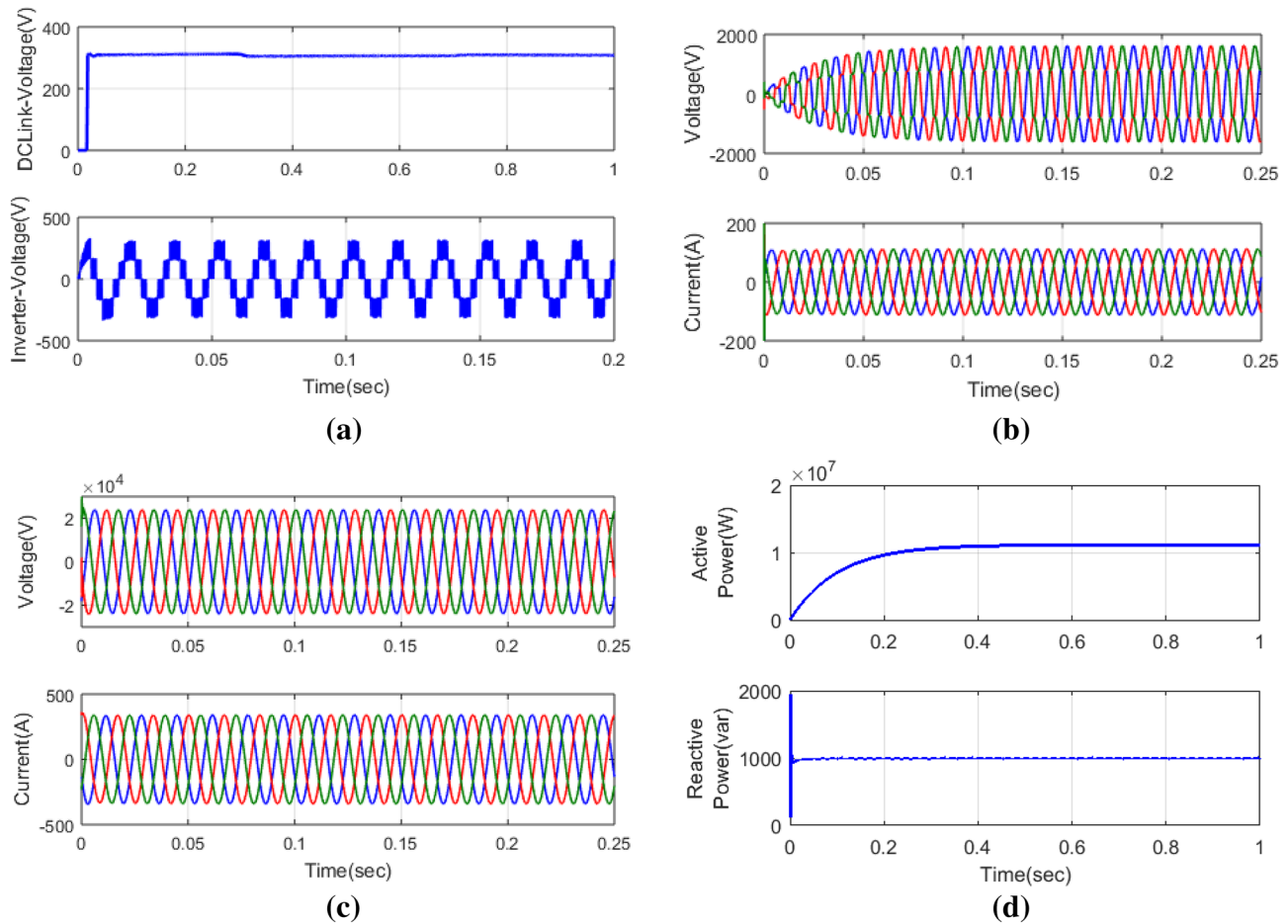
output will be affected so the SSFC can compensate the voltages and stabilize the output power. The two conditions are,

- Condition 1: Constant irradiance and non-linear wind speed condition.
- Condition 2: Linear wind speed and unstable irradiance condition.

In these conditions are applied to the generation side and measures the power parameters. Before that, the normal condition based power parameters are evaluated without using SSFC. Then the SSFC is utilized for compensating the voltages by controlling the control pulse of the SSFC voltage source converters between series and shunt capacitor banks using the adaptive technique. The proposed system is simulated and the results are validating the proposed technique with different conditions. The performance is evaluated conditions are presented as follows.

#### 4.1 Condition 1: constant irradiance and non-linear wind speed condition

In this condition, the power generation of the proposed system is stated to the input and the performances are plotted. Moreover, the stable voltage conservation and the harmonic distortion of the renewable power generation system are controlled to generate quality power. Also, the compensation of the voltage of the grid is based on the SSFC device, which consists of capacitor banks and the filter elements. The first input condition, PV and wind generated voltage, current and power, SSFC voltage and current of the proposed system is presented in Fig. 5. The performance analysis of solar constant irradiance 1000 (W/m<sup>2</sup>) and non-linear wind speed (15, 18, 12 m/s) is considered as condition 1. Based on the condition of the generated voltage, current and power of the PV and wind are evaluated as 50 KW and 1 MW respectively. Then the corresponding SSFC voltage and current also estimated as 50 kV and 200 A.



**Fig. 8** The response of **a** DC-link and inverter voltage, **b** load voltage and current, **c** grid voltage and current and **d** active and reactive power in condition 2

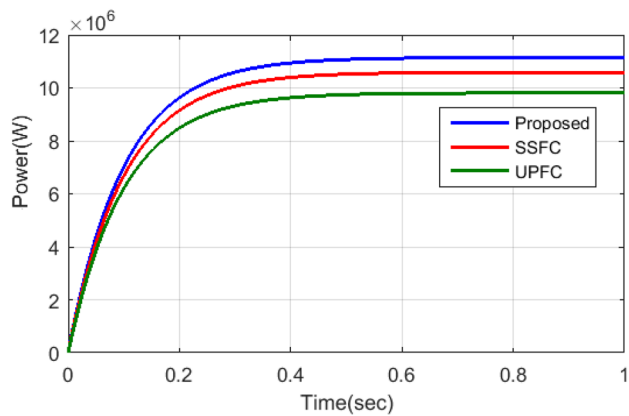
The output response of the proposed system is based on the DC-link and inverter voltages, load voltage and current, grid voltage, current, active and reactive power are illustrated in Fig. 6. The DC-link and inverter voltage is measured as 300 V also the load current and voltage is as 1.5 kV and 100 A respectively. Then the corresponding grid power parameters are evaluated as the voltage is 27 kV, current is 375 A, active power is 10.1 MW and reactive power is 1KVAR. From the above evaluation is showed the effectiveness of the proposed system in the constant PV irradiance and non-linear wind speed variations. The next condition is evaluated as follows.

#### 4.2 Condition 2: linear wind speed and unstable irradiance condition

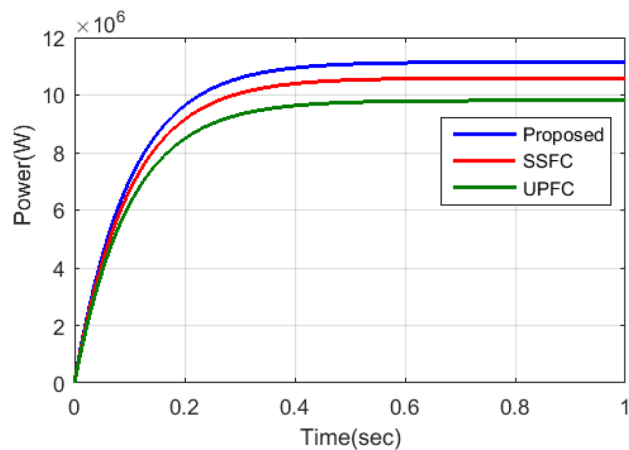
In this condition, the PV irradiance is unstable as 1000, 500, 700 ( $\text{W}/\text{m}^2$ ) and the linear speed of wind 15 m/s. The evaluated parameters as input condition and corresponding

generated voltage, current and power from PV and wind then the voltage and current of SSFC is illustrated in Fig. 7. From the unstable irradiance and the linear wind speed condition the generated voltage, current and power from the PV and wind is measured also defined as the power is 25–50 KW and 1 MW respectively. The SSFC voltage and current are measured as the 50 kV and 200 A, based on the irradiance variation the generated power has some variations.

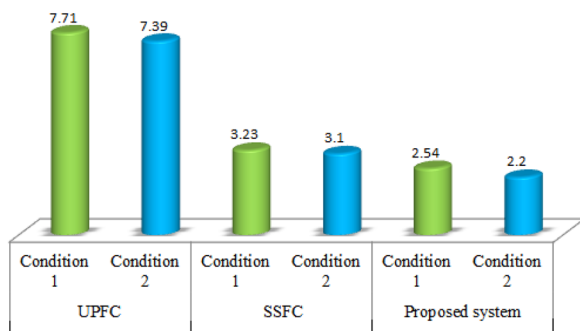
In this condition, the voltage stability improvement and a decrease of harmonic distortion of the system process and the simulated results are examined by using the proposed system of adaptive technique based SSFC. The SSFC can compensate the voltage for regulating the power and given to the linear and non-linear load, induction motor and grid also the corresponding power parameters are illustrated in Fig. 8. In this grid required power is 10 MW that is maintained by the proposed adaptive technique based SSFC device. Finally, the proposed system compared with some traditional power devices that are presented in the followed section.



(i)



(ii)



(iii)

**Fig. 9** The comparative performance evaluation of power in **i** condition 1, **ii** condition 2 and **iii** THD

### 4.3 Comparative analysis of proposed system

The comparison analysis of the proposed system is performed with the UPFC and traditional SSFC from the parameter of active power and THD of the output voltage. The two conditions of output power variation also the THD is described as Fig. 9. From this analysis, the proposed

adaptive technique based SSFC system is giving a good performance from any input or output variations.

From these figures, it is understood that the grid side voltage is reserved at the rated value and the active power. Also, the THD of the proposed system is less in both conditions as 2.54 and 2.2 respectively. The traditional SSFC device THD is 3.23 in condition 1 and 3.1 in condition 2 also the UPFC device is 7.71 in condition 1 and 7.39 in condition 2. Based on the comparison analysis the proposed system has good performance in THD than other systems. The followed section is concluded with the efficiency of the proposed system.

## 5 Conclusion

The adaptive technique based SSFC was proposed for improving the quality of the power from the PQ disturbance. The power transmission system had a hybrid power generation system integrated with the utility grid. The hybrid power generation system is the composite of PV and wind power generation, moreover, there were linear, non-linear load and induction motors were connected as a load. The performance of the SSFC was improved for the quality of power by controlling the switching pulse of the SSFC switches. The switching pulse was optimized by utilizing the adaptive technique, which was a composite of CFA and RNN algorithms. The RNN was used to enhance the searching behavior of the CFA algorithm. The proposed system was simulated in Intel(R) Core(TM) i5 processor, 4 GB RAM and MATLAB/Simulink 7.10.0 (R2015a) platform. The output response was validated from the generation systems and corresponding output parameters. The effectiveness of the proposed system was evaluated from the grid output power from the UPFC and traditional SSFC. Based on the analysis the proposed system gives higher performance than the other systems that were fit for linear and non-linear variation systems.

## References

- Arabul FK, Arabul AY, Kumru CF, Boynuegri AR (2017) Providing energy management of a fuel cell-battery-wind turbine-solar panel hybrid off-grid smart home system. *Int J Hydrog Energy* 42(43):26906–26913
- Arya AK, Kumar A, Chanana S (2019) Analysis of distribution system with D-STATCOM by gravitational search algorithm (GSA). *Int J Inst Eng (India) Ser B*. <https://doi.org/10.1007/s40031-019-00383-2>
- Benabid R, Boudour M, Abido MA (2012) Development of a new power injection model with embedded multi-control functions for static synchronous series compensator. *IET Trans Gener Transm Distrib* 6(7):680–692
- Chaurasia GS, Singh AK, Agrawal S, Sharma NK (2017) A meta-heuristic firefly algorithm based smart control strategy and analysis of a grid-connected hybrid photovoltaic/wind distributed generation system. *Int J Sol Energy* 150:265–274

- Derrouazin A, Aillerie M, Mekkakia-Maaza N, Charles JP (2017) Multi input-output fuzzy logic smart controller for a residential hybrid solar-wind-storage energy system. *Int J Energy Convers Manag* 148:238–250
- Eesa AS, Brifcani AMA, Orman Z (2014) A new tool for global optimization problems Cuttlefish algorithm. *Int J Comput Inf Eng* 8(9):1235–1239
- Eesa AS, Orman Z, Brifcani AMA (2015) A novel feature-selection approach based on the cuttlefish optimization algorithm for intrusion detection systems. *Int J Expert Syst Appl* 42(5):2670–2679
- El Moursi M, Sharaf AM, El-Arroudi K (2008) Optimal control schemes for SSSC for dynamic series compensation. *Int J Electr Power Syst Res* 78:646–656
- Esfahani MT, Hosseinian SH, Vahidi B (2015) A new optimal approach for improvement of active power filter using FPSO for enhancing power quality. *Int J Electr Power Energy Syst* 69:188–199
- Fairbank M, Li S, Fu X, Alonso E, Wunsch D (2014) An adaptive recurrent neural-network controller using a stabilization matrix and predictive inputs to solve a tracking problem under disturbances. *Int J Neural Netw* 49:74–86
- Farahani M (2012) Damping of subsynchronous oscillations in power system using static synchronous series compensator. *IET Trans Gener Transm Distrib* 6(6):539–544
- Gamaa S, Abdelsalam A, Abdelaziz A (2016) Power system distortions mitigation using switched filter compensator. *Am J Electr Power Energy Syst* 5(6):76–80
- Gandomann FH, Sharaf AM, Shady HE, Aleem A, Jurado F (2017) Distributed FACTS stabilization scheme for efficient utilization of distributed wind energy systems. *Int Trans Electr Energy Syst* 27(11):1–20
- Gayatri MTL, Parimi AM, Kumar AVP (2018) A review of reactive power compensation techniques in microgrids. *Int J Renew Sustain Energy Rev* 81:1030–1036
- Ghorbani N, Kasaeian N, Toopshekan A, Bahrami L, Maghami A (2018) Optimizing a hybrid wind-PV-battery system using GA-PSO and MOPSO for reducing cost and increasing reliability. *Int J Energy* 154:581–591
- Gonzalez M, Cardenas V, Espinosa G (2014) Advantages of the passivity based control in dynamic voltage restorers for power quality improvement. *Int J Simul Model Pract Theory* 47:221–235
- Hua J, Xu J, Cheng KW, Guerrero JM (2018) A model predictive control strategy of PV-battery microgrid under variable power generations and load conditions. *Int J Appl Energy* 221:195–203
- Hussain I, Kandpal M, Singh B (2017) Grid integration of single stage SPV-STATCOM using cascaded 7-level VSC. *Int J Electr Power Energy Syst* 93:238–252
- Kabalci Y, Kabalci E (2007) Modeling and analysis of a smart grid monitoring system for renewable energy sources. *Int J Sol Energy* 153:262–275
- Kamel S, Jurado F, Chen Z (2015) Power flow control for transmission networks with implicit modeling of static synchronous series compensator. *Int J Electr Power Energy Syst* 64:911–920
- Kannan VK, Rengarajan N (2012) Photovoltaic based distribution static compensator for power quality improvement. *Int J Electr Power Energy Syst* 42:685–692
- Kaushal J, Basa P (2018) A novel approach for determination of power quality monitoring index of an AC microgrid using fuzzy inference system. *Iran J Sci Technol Trans Electr Eng* 42(4):429–450
- Kirthika N, Balamurugan S (2016) A new dynamic control strategy for power transmission congestion management using series compensation. *Int J Electr Power Energy Syst* 77:271–279
- Mehrjerdi H, Ghorbani A (2017) Adaptive algorithm for transmission line protection in the presence of UPFC. *Int J Electr Power Energy Syst* 91:10–19
- Modesto RA, da Silva SAO, de Oliveira Junior AA (2015) Power quality improvement using a dual unified power quality conditioner/uninterruptible power supply in three-phase four-wire systems. *IET Trans Power Electron* 8(9):1595–1605
- Mukhopadhyay S, Maiti V, Banerji V, Biswas SK, Deb NK (2017) Dual delta bank TCR for harmonic reduction in three-phase static var controllers. *IEEE Trans Ind Appl* 53(6):5164–5172
- Nandi M, Shiva CK, Mukherjee V (2018) A moth-flame optimization for UPFC-RFB-based load frequency stabilization of a realistic power system with various nonlinearities. *Iran J Sci Technol Trans Electr Eng*. <https://doi.org/10.1007/s40998-018-0157-2>
- Qader MR (2015) A novel strategic-control-based distribution static synchronous series compensator (DSSSC) for power quality improvement. *Int J Electr Power Energy Syst* 64:1106–1118
- Rashad A, Kamel S, Jurado F (2017) Stability improvement of power systems connected with developed wind farms using SSSC controller. *Ain Shams Eng J* 9(4):2767–2779
- Sharaf A, Abdelsalam A (2012) A FACTS based static switched filter compensator for voltage control and power quality improvement in wind smart grid. *Int J Power Eng* 4(1):41–57
- Sharaf AM, Abdelsalam AA (2013) A FACTS-based static switched filter compensator for smart distribution grid. *Aust J Electr Electron Eng* 10(1):65–73
- Su B, Lu S (2017) Accurate recognition of words in scenes without character segmentation using recurrent neural network. *Int J Pattern Recognit* 63:397–405
- Teke A, Saribulut L, Tumay M (2011) A novel reference signal generation method for power-quality improvement of unified power-quality conditioner. *IEEE Trans Power Deliv* 26(4):2205–2214
- Ullah N, Ali MA, Ahmad R, Khattak A (2017) Fractional-order control of static series synchronous compensator with parametric uncertainty. *IET Trans Gener Transm Distrib* 11(1):289–302
- Vinkovic A, Mihalic R (2008) A current-based model of the static synchronous series compensator (SSSC) for Newton–Raphson power flow. *Int J Electr Power Syst Res* 78:1806–1813
- Wang L, Truong DN (2013) Comparative stability enhancement of PMSG-based offshore wind farm fed to an SG-based power system using an SSSC and an SVC. *IEEE Trans Power Syst* 28(2):1336–1344
- Zhang XP (2003) Advanced modeling of the multi-control functional static synchronous series compensator (SSSC) in Newton power flow. *IEEE Trans Power Syst* 18(4):1410–1416

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.