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Reactive power planning with the help of multi-objective genetic algorithm and flexible AC transmission systems devices

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ABSTRACT

In this paper power quality of 3-bus solar-based hybrid system has been presented (where one or more than one distribution generator unit is connected to the grid). The injection of solar power into grid-connected systems creates power quality problems such as current consistency, electrical fluctuations, and inefficient power demand. A power quality control strategy based on a real-time self-regulation method for autonomous microgrid operation has been presented. In this paper solar farm design and satisfactory performance tests such as PV-static synchronous compensator (STATCOM) to improve the power quality of grid-based systems have been presented using the MATLAB/Simulink environment. Pulse width modulator (PWM) with proportional-integral derivative (PID) controller used for frequency control, reactive var compensation is used to control voltage profile. Multi-objective genetic algorithm (MOGA) for reactive power planning (RPP) with the objective of reactive power minimization is introduced. The optimization variables are generator voltage, transformer tap changer, and various operational constraints.

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1. INTRODUCTION

Due to the enormous challenges facing the operation of modern power systems, it is important to maintain reliable power to customers and stay within bus voltage limits while meeting ever-increasing load demands and emergency situations. Many control measures can be taken to reduce the reactive power demand on the system [1]. These include changing the voltage set point on the voltage control bus by controlling the generator excitation, updating tap settings, replacing transformers, shunt capacitors, var static compensators, and flexible AC transmission systems (FACTS) devices [2]. Includes installation of size and location var resources. However, poor reactive power support can lead to voltage drops and even power outages [3].

The techniques used in reactive power compensation may be index-based and optimization-based method, nowadays heuristic optimization methods are used while the former depends on the priority list to reduce solution space [4]. Figure 1 shows the block diagram of the proposed solar-based hybrid system in witch 11-level inverter with a DC-DC boost converter is used has been used to synchronize the solar power to the grid supply. The control strategies for the proposed test system are presented in Figure 2.

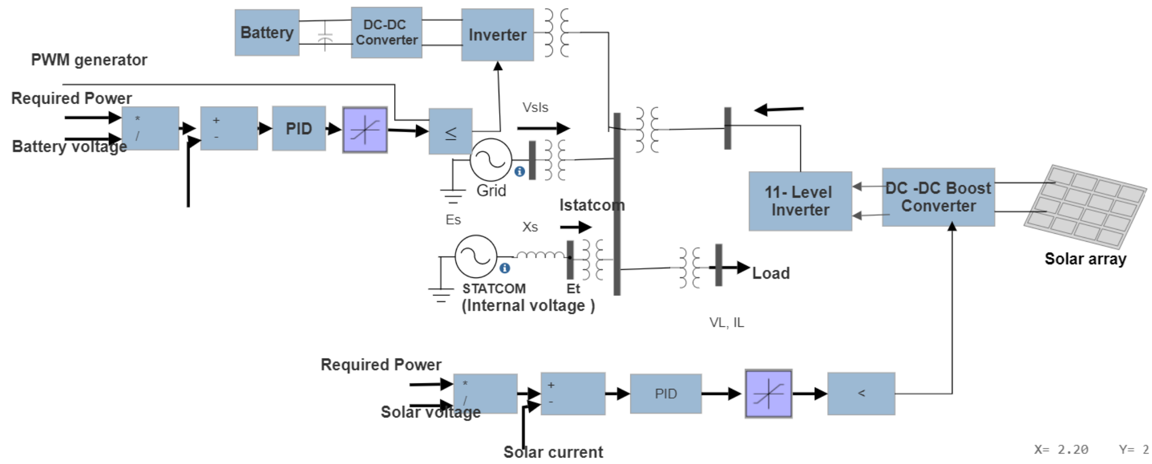

Figure 1. Proposed hybrid system (block diagram)

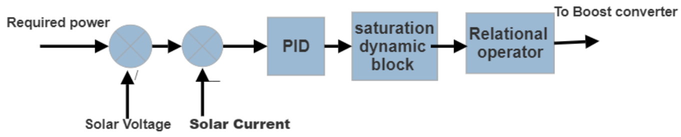

Figure 2. Control strategies for proposed test system

2. METHOD

Multi-objective genetic algorithm (MOGA) has been used to solve the reactive power planning (RPP) problem with the primary objective of minimizing the reactive power demand [5]. With the imprudent of total transfer capacity (TTC) and voltage stability, the distance from current operating conditions to the point of instantaneous voltage drop is increased [6]. More than one reactive var source has been used in the proposed design.

2.1. Modeling of flexible AC transmission systems devices

FACTS devices are used in the power systems to control the power flow and to enhance the voltage profile [7]. FACTS devices also help to reduce transmission losses and enhance the transmission line load ability. Static var compensators (SVCs) and thyristor-controlled series compensators (TCSCs) are two good approaches to use in designs intended for improving voltage stability and reactive power. In addition, SVC and TCSC have fast control response and low investment cost [8], [9]. SVC is shunt variable susceptance that inject var at different bus location as represented in Figure 3. That injected power at particular bus (ith bus) is: $S_{svc,i} = B_{svc,i}\, V_i^2$. SVC is antiparallel silicon-controlled rectifier (SCR) in series with a high value of inductor are connected in parallel with a large capacitance reactance as shown in Figure 3(a). It injected reactive current to the ith bus as shown in Figure 3(b), only when the ith bus is a lower potential than the reference bus (infinity bus).

Figure 3. Static var compensator (a) basic structure and (b) power injection

The practical representation of TCSC is shown in Figure 4. TCSC shown in Figure 4(a) is a capacitive reactance compensator with a series controlled reactor shunted with a capacitor bank. Figure 4(a) represents the implementation of the TCSC connected between the ith and jth bus of the transmission line [10]–[12]. Where R_{line}: line resistance, X_{line}: line reactance, $R_{i,j}$: resistance between bus i and bus j, $X_{i,j}$: reactance between bus i and bus j, $P_{TCSC,j}$: injected active power at jth bus, $Q_{TCSC,j}$: injected reactive power at jth bus, $P_{TCSC,i}$: injected active power at ith bus, $Q_{TCSC,i}$: injected reactive power at ith bus, Bj: susceptance of line (Figures 4(b) and (c)), V_i: voltage at ith bus (static synchronous compensator (STATCOM) connected at ith bus), and V_s: voltage at infinite bus bar. Table 1 represents the design parameters of the proposed MATLAB module that will help us to analyze the model. For inductive load lagging power factor transmission line absorbed reactive power whereas for leading load transmission line supply reactive VAR and absorbed active power (shown in Table 2). FACTS devices normally use in transmission lines to inject or absorbed the reactive power (Table 3). The injected power can be represented as (1)-(4):

$$P_{TCSC,i} = |V_i|^2 \Delta\, G_{ij} - |V_i||V_j|\left(\Delta G_{ij}\, \cos(\delta_{ij}) + \Delta B_{ij}\, \sin(\delta_{ij})\right) \tag{1}$$

$$Q_{TCSC,i} = -|V_i|^2 \Delta\, B_{ij} - |V_i||V_j|\left(\Delta G_{ij}\, \sin(\delta_{ij}) - \Delta B_{ij}\, \cos(\delta_{ij})\right) \tag{2}$$

$$P_{TCSC,i} = |V_j|^2 \Delta\, G_{ij} - |V_i||V_j|\left(\Delta G_{ij}\, \cos(\delta_{ij}) + \Delta B_{ij}\, \sin(\delta_{ij})\right) \tag{3}$$

$$Q_{TCSC,j} = -|V_j|^2 \Delta\, B_{ij} + |V_i||V_j|\left(\Delta G_{ij}\, \sin(\delta_{ij}) + \Delta B_{ij}\, \cos(\delta_{ij})\right) \tag{4}$$

Where $P_{TCSC,i}$, $P_{TCSC,j}$, $Q_{TCSC,i}$, $Q_{TCSC,j}$ may be positive or negative due to installing the TCSC in branch (i-j). The steady-state model and power-injected model of TCSC are represented in Figures 4(b) and (c) susceptance (ΔB_{ij}) in between ith and jth bus can be calculated as (5) and (6):

$$\Delta G_{ij} = \frac{-X_{TCSC}\, R_{ij}(X_{TCSC} - 2X_{ij})}{\left(R_{ij}^2 + X_{ij}^2\right)\left[R_{ij}^2 + (X_{ij} - X_{TCSC})^2\right]} \tag{5}$$

$$\Delta B_{ij} = \frac{X_{TCSC}\left(R_{ij}^2 - X_{ij}^2 + X_{TCSC} X_{ij}\right)}{\left(R_{ij}^2 + X_{ij}^2\right)\left[R_{ij}^2 + (X_{ij} - X_{TCSC})^2\right]} \tag{6}$$

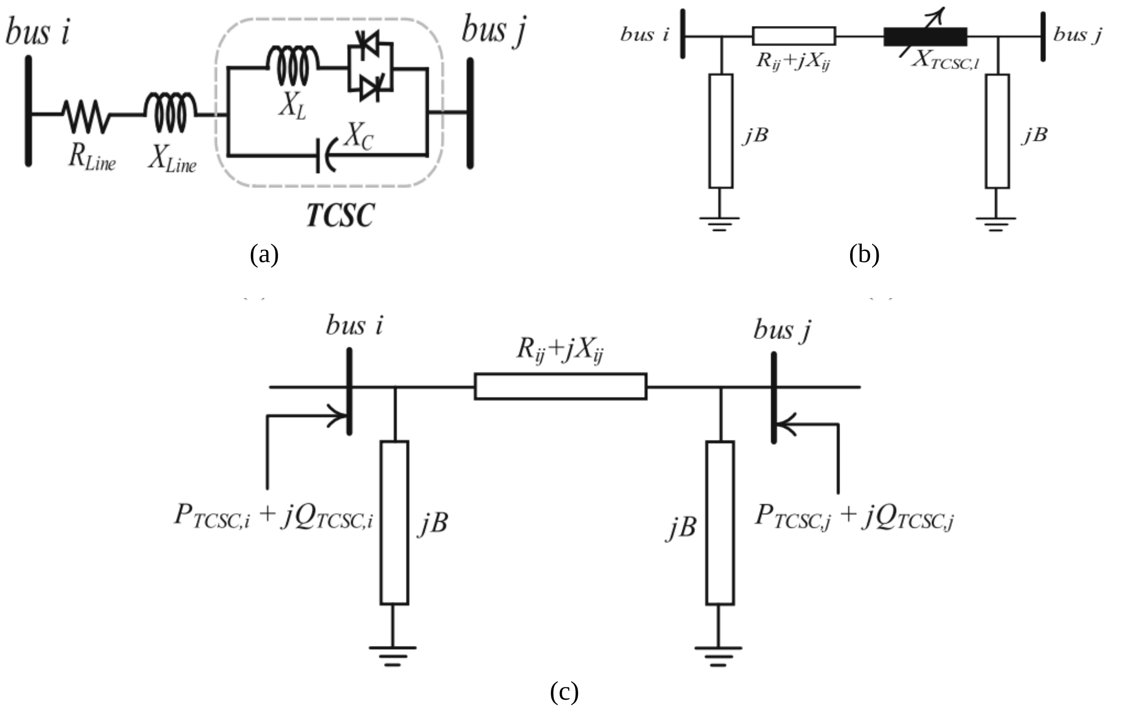

Figure 4. Thyristor-controlled series compensator (a) basic structure, (b) steady-state model, and (c) power injection model

2.2. Proposed algorithm [13]–[15]

The proposed algorithm steps are: i) collect the bus data (no of bus generator bus, load bus, and line reactance), ii) run the load flow program, iii) find reactive power planning problem in proposed design. If it's, identify the control variables. If it's not, stop the algorithm, iv) selection of MOGA parameters, v) randomly initialized the population at a bus, vi) run the power flow again with updated system data, vii) update objective function, viii) check the system constrain, ix) repeat step 6 to 8 and increment the generation count until the count reached the maximum value, and x) stop the algorithm and print the result. The contributions of present work are: a new MOGA approach to solving the RPP problem to minimizing the reactive power demand [16], [17]. The optimal allocation of new var resources is considered as the control variable rather than their placement on the weakest bus.

Table 1. System parameter description

S. No	Parameters	Ratings
1	AC-source	3-phase, 415 V, 50 Hz
2	Line inductance	0.05 mH
3	Shunt inductance	0.65 mH
4	Load	Three phase, 50 kW
5	Inverter parameter	C=5 mF, DC link voltage=750 V
6	Solar plant	17 kV
7	Insulated gate bipolar transistor (IGBT) rating	Gate voltage =20 volt, I, 50 A, collector voltage=1,200 V

A RPP problem is a mathematical formulation that can be viewed as a simple attempt to find an optimal solution to an objective function through a set of controllable variables [18]. This includes minimizing his new var resources and improving his TTC. The ultimate goal of MOGA is to identify a solution on a Pareto-optimal set [19].

The behaviours of PV STATCOM are presented in Tables 2 and 3, it absorbed reactive var and delivered reactive var too according to voltage and reactive var at the infinite bus. The VSC-based PV shunt active power filter (APF) provides the effective and efficient power required for the grid-connected test model to minimize power quality distortion. PV STATCOM contains various components such as DC bus capacitors (C_{dc}) and interface inductors (L_f). The following is an excerpt or test of a few segments of PV-based APF [20].

Table 2. Modes of operation of PV–STATCOM (capacitive and inductive mode) [21]–[23]

Case	Mode	Operation
$V_s > V_i$	Inductive mode	Absorbing reactive power (Q)
V_i lags V_s by phase Ø		Supplying active power (P)
$V_s > V_i$	Inductive mode	Absorbing reactive power (Q)
V_i leads V_s by phase Ø		Absorbing active power (P)
$V_s > V_i$	Capacitive mode	Supplying reactive power (Q)
V_i lags V_s by phase Ø		Supplying active power (P)
$V_s > V_i$	Capacitive mode	Supplying reactive power (Q)
V_i lags V_s by phase Ø		Absorbing active power (P)

Table 3. Active and reactive power injection and absorption by PV STATCOM

Case	Inverter power
Reactive power Q< 0	Absorbing reactive power (Q)
Reactive power Q>0	Supplying reactive power (Q)
Active power P<0	Absorbing active power (P)
Active power P>0	Supplying active power (P)

2.3. Higher level inverter

An inverter is an electronic circuit used to convert direct current into alternating current. Other parameters such as output power, current, frequency and harmonic components present in the output power depend on the design of the converter and the type of input power supply [24]. Multilevel converters have gained importance in recent decades. These new types of inverters can synthesize waveforms with better harmonic spectra and lower total harmonic distortion (THD), making them suitable for high voltage and high power applications. Many topologies have been introduced and extensively studied for their utility and propulsion from unconventional sources [25]. Three-phase multilevel inverters have fewer gate drive circuits, lower cost, less heat, easier installation, and less electromagnetic interference. The LC series passive filter is designed to generate a sine wave from the output of the shunt inverter [26]. The purpose of the output LC filter is to dampen the voltage ripple due to the switching of the inverter.

2.4. The main feature of 11-level inverters

It has the ability to minimize voltage stress due to the utilization of multiple levels on the DC bus. Higher-level inverters are more important when high DC side voltage is imposed like a traction system. With the help of a higher-level inverter at a very low frequency, smaller distortion can be achieved at the AC side [27]. The IGBT switches are controlled to control the triggering cyle of IGBT, the control circuit (block diagram) is represented in Figure 5. Where grid voltage is compared with a reference voltage after that error is minimized with help of a proportional integral derivative (PID) controller.

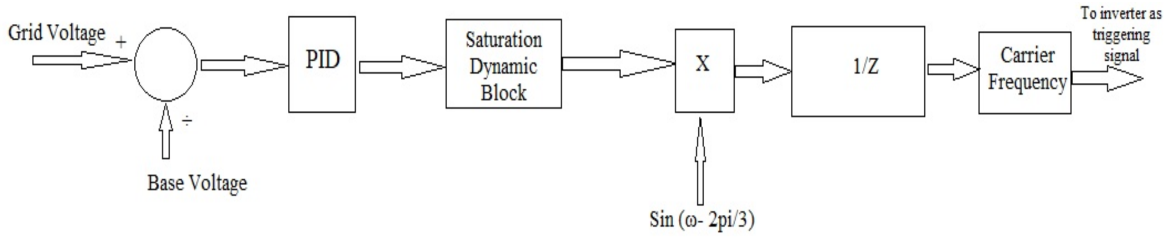

Figure 5. 11-level inverter control

Cascading of N single phase H bridge inverter with N number of dc source gives a cascaded multilevel inverter (shown in Figure 6) [28]. (2N+1) level inverter requires N number of dc sources equal in magnitude. The cascaded multilevel inverter can produce high voltage magnitude with fewer harmonic from a low voltage input [29]–[31].

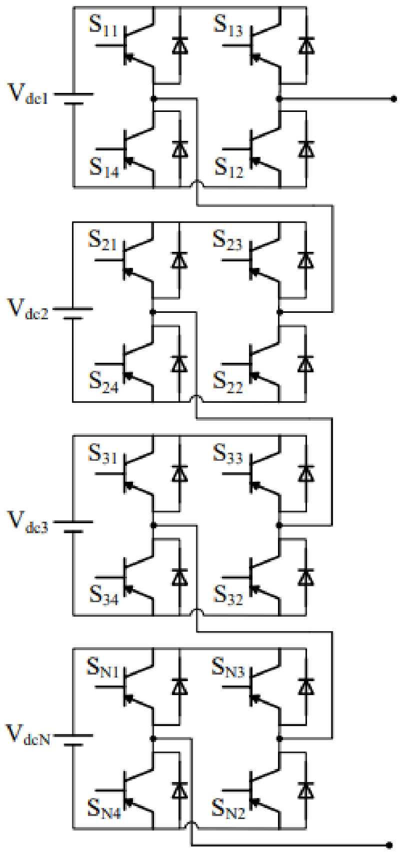

Figure 6. Cascaded (2N+1) level inverter

The fundamental output voltage in terms of the switching angle:

$$V_1 = \frac{4V_{dc}}{\pi}(\cos(\alpha_1) + \cdots + \cos(\alpha_s)) \quad (7)$$

Where S is no of switches and n is order of harmonics. The output line to line voltage (only non-triple odd harmonics are present).

$$v(\omega t) = \sum_{n=1,5,7,11....}^{\infty} \frac{4V_{dc}}{n\pi}(cosn\alpha_1 + cosn\alpha_2 + \cdots + cosn\alpha_S)\sin\ (n\omega t) 0 < \alpha_1 < \alpha_2 < \ldots \alpha_s < \frac{\pi}{2} \quad (8)$$

$$\text{Total harmonic distortion } = \sqrt{\sum_{i=1,5,7,11...}^{49} \left(\frac{V_i}{V_1}\right)^2} \quad (9)$$

2.5. DC bus capacitor

PV STATCOM consists of DC capacitors used to deliver a constant voltage to the power source converter (VSC). The DC bus voltage V_{dc} is calculated with the expression:

$$V_{dc} = \frac{2\sqrt{2}\times V_{line}}{\sqrt{3}\times m} \quad (10)$$

V_{line} is the inverted line voltage, m is the modulation index, V_{dc} should be greater than inverted voltage for successful PWM control of shunt active power filter. For V_{line} 415 volts, V_{dc} =677.69 volt. Size of DC bus capacitor has been designed based on depression in its voltage due to application of load and rise in dc voltage on load condition.

2.6. Multi-objective genetic algorithm

The genetic algorithm is a generalized search algorithm based on the dynamics of natural genetics. A genetic algorithm manages a population representing possible solutions to a particular task. Based on the objective function, each individual in the population is assigned a fitness for a certain problem [32]. Genetic algorithms combine solution evaluation with stochastic operators (selection, crossover, mutation) to achieve optimality [33]. As a population approach, GA is suitable for solving multi-objective optimization problems. The joint optimization of several objective functions of a real problem (these functions are not commensurable and contradict each other) can be solved using multi-objective genetic algorithms [34]. Multi-objective optimization with such competing objective functions leads to a series of optimizations rather than a single optimization. The reason many solutions are optimal is that they are unlikely to outperform others in all objective functions. These optimal solutions are called Pareto optimizations. The set of Pareto solutions is called the Pareto set, and their image in the space of objects is called the Pareto front. The leading solution in the problem search space is worse than at least one other solution for all defined objectives [35]. A non-dominant solution is called a Pareto optimal solution. The set of all non-dominant solutions forms the Pareto frontier representing the optimal trade-offs that exist between competing objectives.

There are several approaches to solving multi-objective optimization problems. Aggregation, non-Pareto populations and Pareto-based techniques. Aggregation methods usually use weighted or goal-based methods to combine different goals into one [36]. The vector valued genetic algorithm (VEGA) is a non-Pareto population approach that uses different subpopulations for different purposes. MOGA, nondominant sorting genetic algorithm (NSGA), and special Pareto genetic algorithm (NPGA) constitute number of techniques within the non-elite Pareto approach. Aggregation methods usually combine different objectives into one using weighted or objective-based methods.

2.7. Interfacing inductor

The design of interfacing inductance L_f depends on switching frequency (f_s) and ripple current (i_{crpp}), the interfacing inductor can be calculated as (11):

$$L_f = \frac{1.732\times m\times V_{dc}}{12\times a\times f_s\times i_{crpp}} \quad (11)$$

The capacitor (5 μF) and resistance (5 ohm) in series with interfacing inductor are acting as ripple filter [37]. The combination is the first order high pass filter which removes high frequency noise. Table 4 variation of power quality parameter with and out 11-level inverter. Table 5 represents the power quality parameters in existing research papers [38], [39].

Table 4. Power quality parameters

Power quality parameters	Without 11 level inverters	With 11 level inverters
Vr (pu)	0.01	0.0304
Vy(pu)	0.037	0.03079
Vb(pu)	0.047	0.06125
THD	0.9851	0.8022
pf	0.9804	0.9006
Frequency	50	50.12

Table 5. Power quality parameters comparison with existing literature

Power quality parameters	Proposed work	Existing literature
THD	0.8022%	1.29%
pf	0.9006	Near unity
Frequency	50.12	50-50.4

3. RESULTS AND DISCUSSION

MOGA is used to solve the RPP problem and aims to achieve higher stability with better power quality using capacitor banks and FACTS devices. The results obtained by the proposed approach are compared with the results reported in the literature. Solar generated voltage is a DC voltage to synchronize with grid 11 level inverter has been used Figure 7(a) shows the inverted solar voltage whereas Figures 7(b)-(d) show the load voltage, RMS load voltage and angular frequency (grid angular frequency) respectively. Figure 7(e) shows the grid frequency with a constant magnitude 50 Hz. The constant magnitude of frequency shows the feasibility of the system. Grid voltage for the load range 10 kW to 150 kW has been checked (Figure 8) are nearly sinusoidal. THD is an important parameter to judge the power quality of a power system. Figures 9 and 10 show the THD in power supply with 11-level inverter and STATCOM, without 11-level inverter and STATCOM respectively. THD of Figure 9 is very less compared to THD in Figure 10. Less THD shows the better power quality. The magnitude of THD has been shown in Tables 4 and 5 (with 11-level inverter-STATCOM and without 11-level inverter-STATCOM). Pareto optimization for the optimization of reactive var is shown in Figure 11 (multiobjective optimization). Grid frequency are nearly constant and equal to 50 Hz (for load range 10 kW to 150 kW) shown in Figure 12.

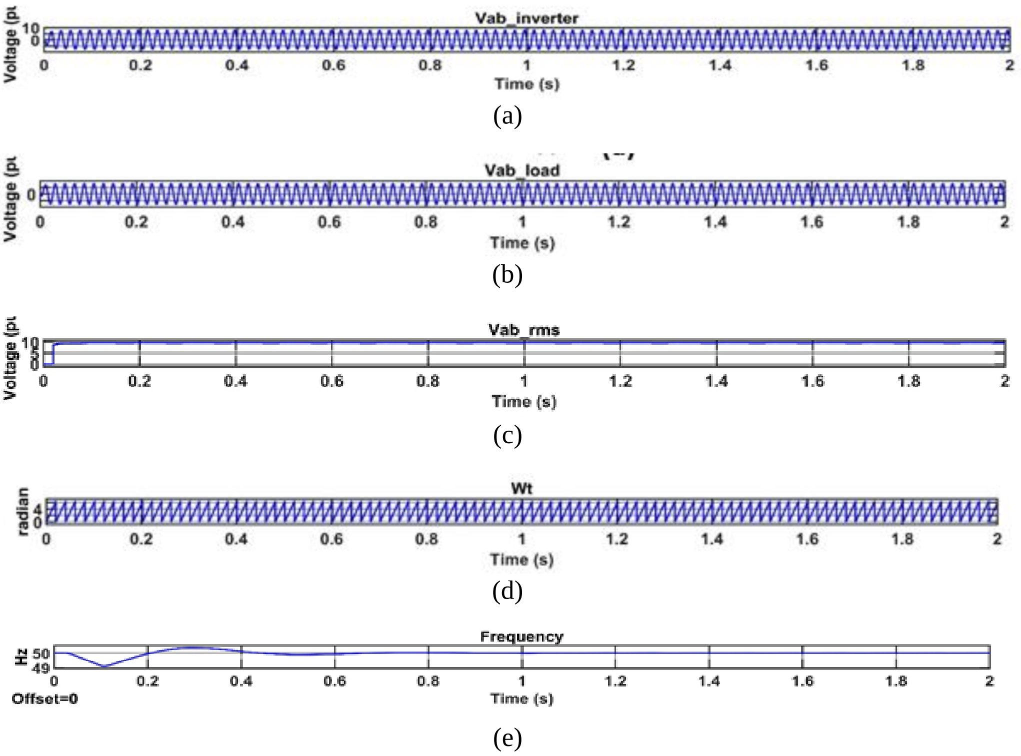

Figure 7. Voltages and frequancys of desined system (a) inverted solar voltage, (b) load voltage, (c) load RMS voltage, (d) angular frequency in radian, and (e) grid frequency

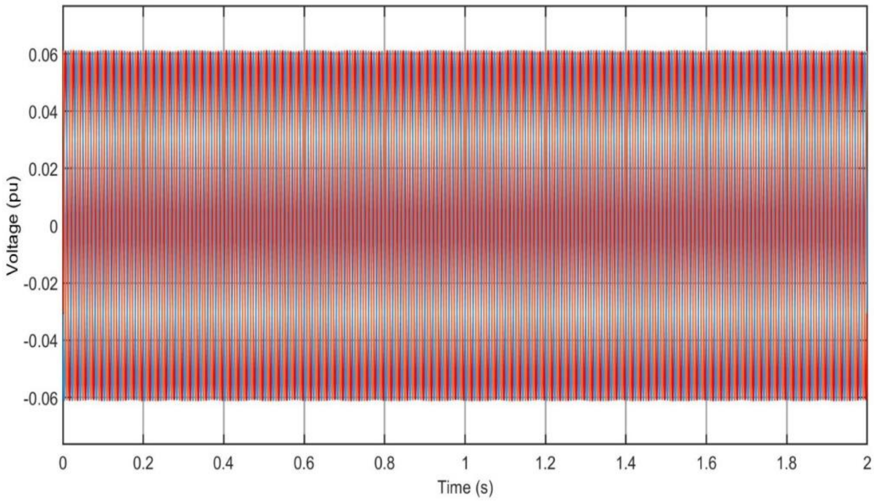

Figure 8. Grid voltages

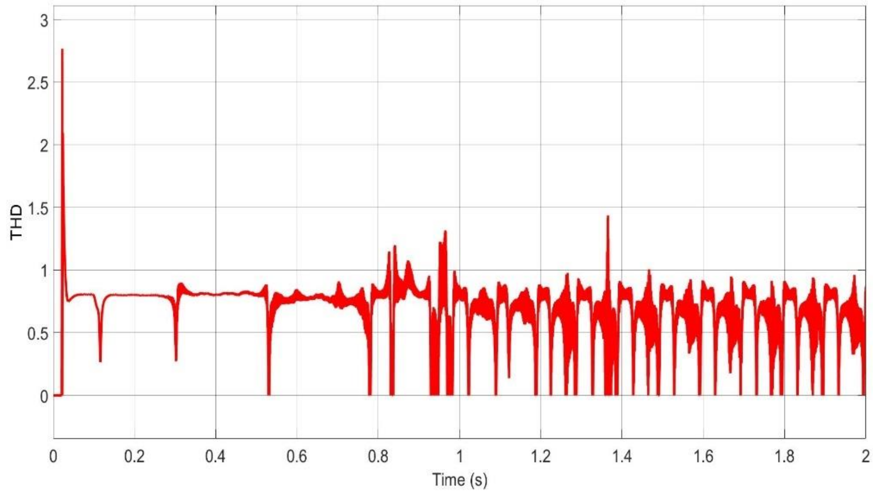

Figure 9. THD in power supply with 11-level inverter and STATCOM (using MOGA)

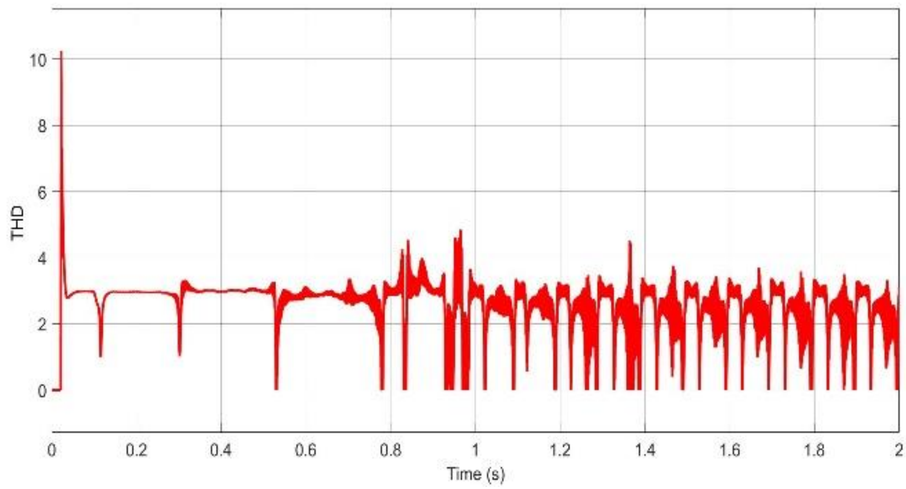

Figure 10. THD in power supply without 11-level inverter and STATCOM

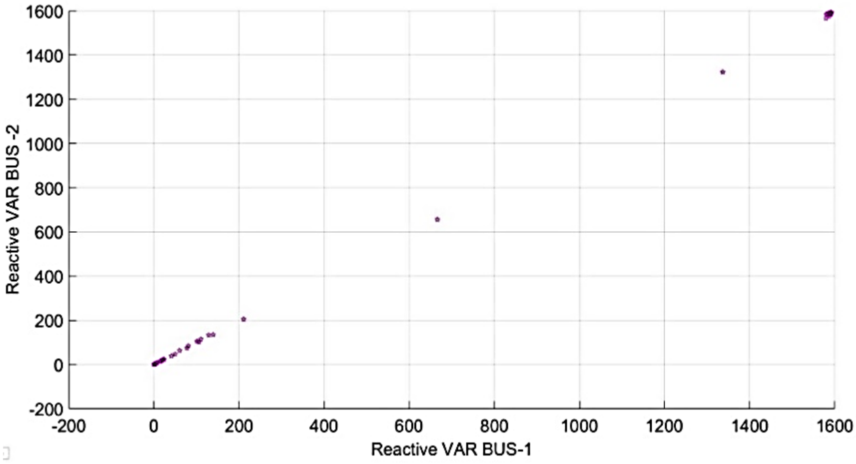

Figure 11. Minimization of reactive var (Pareto optimization)

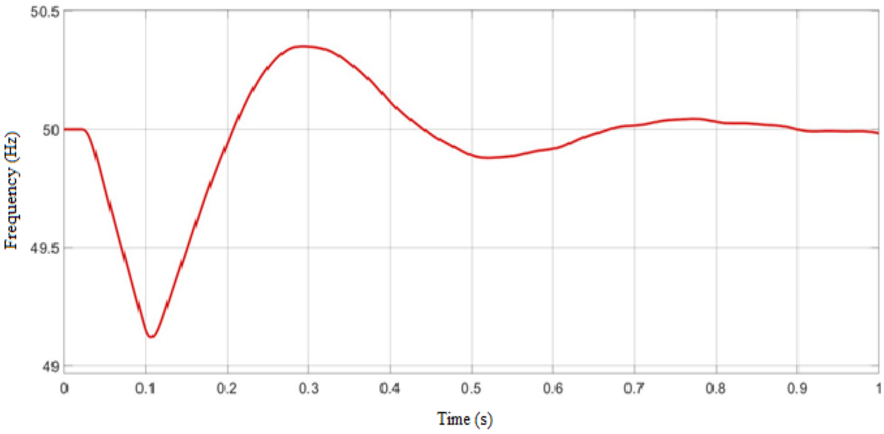

Figure 12. Grid frequency

4. CONCLUSION

In this work, MOGA is used to solve the RPP problem with objective minimization of reactive power demand. It has been seen that var source devices improve the system voltage stability. The proposed approach has been tested on 3 bus solar-based hybrid system and the performance of the designed system is getting up-to-date and satisfactory. It has been seen that the use of capacitor bank, and FACTS devices (STATCOM) propose required compensation for a lack of reactive var in the system, It also improve power quality in grid-tied systems. The use of a capacitor bank is not the best option to enhance the voltage profile (Improve the power quality parameters) while the use of FACTS devices (STATCOM) is the best to enhance the voltage profile and he so power quality. The use of a higher-level inverter with STATCOM gives better power quality in proposed 3-bus hybrid systems.

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