UNIVERSITY of RWANDA COLLEGE OF SCIENCE AND TECHNOLOGY ACE-ESD AFRICAN CENTER OF EXCELLENCE IN ENERGY FOR SUSTAINABLE DEVELOPMENT

APPLICATION OF STATIC VAR COMPENSATOR (SVC) FOR IMPROVING POWER QUALITY OF GRID CONNECTED SOLAR ENERGY

By

Marie Grâce BERWA (BSc)

Registration Number: 220009724

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Dissertation Advisor: Dr Peter Musau Moses, PhD

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DECLARATION

I, the undersigned, declare that this dissertation is the result of my own work, and has not been submitted for any other degree at the University of Rwanda or any other institution. All sources of materials that will be used for the dissertation work will have been fully acknowledged.

Printed Name: Marie Grâce BERWA

Signature:

Date of Submission: 22nd October, 2021

This dissertation has been submitted for examination with my approval as a university advisor.

Dr Peter Musau Moses, PhD

Dissertation Advisor

Signature

DEDICATION

This dissertation is dedicated to ***my beloved husband Jean d'Amour Uwiduhaye, my children Béni Gali Rukundo,*** *and* ***Ariel Malo Rukundo*** *for their inspirational encouragement to my education, despite all the economic difficulties. All my educational successes are recognized to a great extend for their beliefs in the value of education. I am frankly thankful for having you in my life.*

This work is also dedicated to the memory of ***my late father*** *who always showed me the value of education and to* ***my mother*** *who have always loved me unconditionally.*

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ABSTRACT

Application of Static Var Compensator (SVC) for Improving Power Quality of Grid Connected Solar Energy

By

Marie Grâce BERWA (MSc)

The University of Rwanda, 2021

The green/renewable energies are being developed rapidly worldwide. Promoting renewable energies has benefits not only for the environment but also for the economic conditions of the country. The integration of renewable energy sources into power systems is a key perception of smart grids. Remarkable challenges affecting the system of integration include voltage instability, frequency instability, and general power quality. Real power drop and voltage divergence minimization are measures of voltage security of power system grids. To control system voltages, recover transient stability, upsurge transmission capacity, etc. the SVC's are suitable. The work recommends the optimal usage of the SVC in the enhancement of the voltage stability. The challenging of voltage collapse has been expressed as an optimization problem based on the process of particle swarm optimization (PSO) technique. This technique is applied in the study of voltage stability and power losses of the power system. The optimal introduction of SVC with particle swarm optimization technique presented a noticeable enhancement in the voltage stability with a comparatively small number of iterations and particles, therefore with a practical computational effort. The success of the projected algorithm is confirmed on IEEE-14 Bus standard test system. The proposed optimization method proved to be more effective and efficient in voltage stability and power loss reduction in the PV grid connected system.

Keywords: Power System, Voltage Stability, Particle Swarm Optimization, SVC

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CHAPTER 1

INTRODUCTION

1.0.Background of the Study

Nowadays, the world is developing energy sources other than fuel fossil and gas to mitigate the global warming that is affecting health of the population, the cloud weather, water pollution, animals as well as vegetation. The green/renewable energies are being developed rapidly worldwide. The photovoltaic (PV) energy is an attractive renewable energy with abundance in sunlight worldwide and its use has increased to 7% in 2017. It is expected to reach 23% in the year 2040 [1]. Contrary to other renewable energy sources like wind power, the distribution of photovoltaic power is easily integrated into the electrical network at any point.

Integrating renewable-energy sources in the power systems is a key perception of smart grids. The integration of standardized solar power systems into the distribution system minimizes the functional costs, improves economically the solar system, improves energy balance and finally gives an added value to the absorbers and service. In different countries, PV-grid integration is significantly and widely used following the increase of using clean energy compared to fossil fuel [1].

PV power systems are mainly grouped into two groups including free-standing and connected to the grid systems. A PV grid-connected comprises the Photovoltaic array, DC-DC converter(s), inverter(s), meters, grid connection as well as DC and AC wiring. The inverters are the most important elements for the integration. The grid-connected PV systems can be classified based on power rate or module configuration. Among the required considerations and focus in this process, include installations, operations and the areas of solar constituent assemblage. It has different benefits including cost effective as the batteries are not used, less maintenance among others.

By the way of an increasing request for the use of different clean energy which produce tidy, self-assured, economic and harmless energy as against fossil fuel; solar-grid integration is nowadays shared in several countries worldwide. The statistical capacity in Renewable Energy (IRENA, 2017) shows that the Africa is the least continent with an installed total solar capacity equivalent to approximately 2.5 GW, constituting not more than 1.16% of the total solar installed capacity globally [1] although Africa is receiving solar radiation abundantly.

Based on geographical location of Rwanda, the country is generally characterized by Savannah climate and sufficient solar radiation intensity, which ranges from nearly 4.3 to 5.2 kWh/m^2/day ([2], [3]) at an average of approximately 5 hours sunshine a day, which makes solar energy economically viable. It reveals that potentials for solar exist but is not yet exploited. Results from an assessment conducted by the National Air and Space Agency (NASA) of the United States together with the University of Rwanda revealed that the promising area in terms of generating energy from the solar sources is the Eastern Province of the country ([4], [5]). Currently, 12.08 MW from solar energy is on-grid representing share of 5.5%.

Presently, the grid has settings that can be used to switch voltage and brand the grid steadier; the innovative inverters devices change DC solar power to AC power. In spite of replacing load parameters, as well as want to supply and also engross the reactive power with reference to reactive loads, the inverters are vital to supplying continuous frequency and voltage.
A PV installation yield reliant on the reliability and the inverter's efficiency by the way of orientation, interconnection as well as the quality of PV modules. Notable challenges affecting the system of integration include voltage instability, frequency instability, and general power quality. In solar energy the two deviations are the main challenges in grid integration; voltage and frequency are not constant due to the quantity of irradiance.

The Static Volt-Ampere Reactive Compensator (SVC) needs reactors to absorb VARs from the system, in case the reactive load of the system is found to be capacitive (leading) the voltage will be reduced. Below lagging (inductive) situations, the capacitor banks will immediately switched in, therefore giving high voltage of the system [6]. To control system voltages, recover transient stability, upsurge transmission capacity, etc. the SVC's are suitable.

1.1. Problem Statement

In solar energy, it is difficult to share power into the system. Power quality, availability of power, change in power, voltage stability are the numerous problems in this incorporation. In this study, the method of applying a static VAR compensator (SVC), which is an electrical device used to provide fast-acting reactive power upon high-voltage transmission systems, control the voltage, improve the power quality and balance the system.

1.2. Research Objectives

1.2.1. Major Objective

The foremost aim of the present thesis is to apply a static Var compensator to enhance the voltage of solar energy connected to the grid leading to its power quality.

1.2.2. Specific Objectives

i) To design a system that improves and stabilizes the power grid using a static var compensator.

ii) To design a fast-acting dynamic reactive compensation this delivers voltage support in contingency situations.

iii) To design a system that will minimize the power system losses during fluctuations.

1.3. Research Questions

i) This study examines the practice of an SVC used together with solar energy for the drive of appropriate settling down the network.

ii) What is the contribution of SVC to the stability of solar grid connected?

iii) How can SVC improve the power quality of solar grid connected?

iv) How can SVC reduce the real power losses?

1.4. Justification of the Study

Due to large transmission networks, usage of diverse renewable energy types and various load patterns, modern power systems are experiencing violation in functioning limit and voltage fluctuation troubles. As the power system must be operated with intend of maintaining the channel power and the voltage on each bus is at the limit of its operations. The capability of a power system to sustain the system voltage in adequate range at all buses and even after experiencing a disturbance is called the voltage stability. The voltage instability is defined as the overload of the system in transmission lines and shortage in local reactive power sources.

The significance of this work, once the SVC used, it will improve the power system voltage stability due to suitable compensation recovers and reducing power losses. The optimal outline of SVC with particle swarm optimization technique will present a visible improvement in the voltage stability.

1.5.Scope of the Study

The power quality improvement of solar energy connected to the grid using star var compensator will focus on voltage stability enhancement and reduction of real power losses.

1.6.Conceptual Framework

This section presents the thesis framework for voltage instability improvement using PSO in figure below.

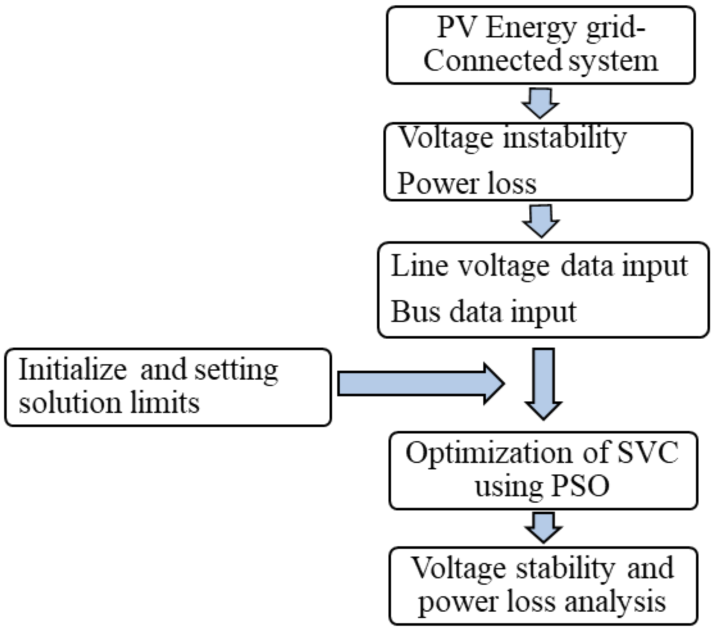

Figure 1.1Conceptual framework for PV grid-connected for improving voltage and minimize power loss

Moreover, the simulation results revealed that the voltage balance of the system integrated with solar energy could be improved

1.7.Thesis Organization

This study comprises five chapters presented as follows; chapter one consists of introduction that covers background of the study, problem statement, aim of the study, research questions, scope of the study and report organization. Second chapter consists of literature review. Chapter three consists of methodology that comprises introduction, research design, methodology. Chapter four is dedicated to design, results and analysis. Chapter five comprises the conclusion and recommendations.

CHAPTER 2

LITERATURE REVIEW

2.0. Introduction

The chapter illustrates the problem faced in renewable energy integration and possible solution by using power electronic device. For the preceding power grid, solar-grid integration plays a vital role to solar power generated from photovoltaic or concentrated solar power (CSP) system. Many attentions required for the integration of solar energy to grid such as solar module manufacturing, connections, and operation among others. The solar energy needs to be unified efficiently on the transmission grid; such interconnection considering the belongings of the grid at numerous facts. A significant development found in power system operation and control was introduced.

2.1. Power Quality Problems in PV System Integration

Integration of solar power to electricity public network has been used widely in recent years. This is accelerated by state and countries' goals in using renewable energy sources. Renewable energy integration is defined as the way of mixing the green energy power to the public grid. Conventional/ unconventional power plants and renewable energy plants like solar are the two-input generation of alternating current (AC) grid, and for meeting the integration settings the output power from renewable energy must stay an alternating current power. Photovoltaic plant encompasses different elements but the very important element for integration is the inverter [1]. The main function of an inverter is to invert the direct output to alternating current, which makes typically use by different devices. The inverters play essential role in supplying steady voltage and frequency, in spite of exchanging load environment, also require supplying, alternatively reactive loads absorbing reactive power. Most of large-scale PV is situated distant from urban centers, the transmission lines are desired to transmit the electricity generated to the end user. Additional investment in construction of transmission lines is compulsory.

Photovoltaic power generation does not take the advantage of making power on request due to variation of climate [1] but the conventional power plants have the benefit to spin a turbine to control over generation. The power inverters used to convert renewable generated direct current voltage into AC are the key cause of harmonics issues. The loads that present frequency that are multiples of 50 or 60Hz generate harmonics and can cause equipment not to work as planned. Power quality problems range from voltage and frequency then expanses toward harmonics. The characteristic of photovoltaic systems permits variations of voltage generated that have not previously be in the grid. The power demands from the consumers present a very different characteristic and the accessibility of renewable energy sources has strong daily and seasonal dependent. Therefore, it is difficult to run a power system connected with only renewable generation units due to the typical changes and the high doubt in the accessibility of the renewable energy sources [7]. A grid connected voltage quality problems must be measured together with the intermittency of PV generation.

Integration of PV power to national distribution grids causes negative effects on its power quality, its reliability as well as the stability of the electricity network. Another impact is related to the bidirectional power flow from the protection of the equipment issues. From the design of the circuit, with the electrical installation position, have some impact on the voltage changes, network steadiness, voltage control, safety, power quality and harmonization.

Contrary to conventional power plants, PV power plants lack rotor, therefore no inertia is present; the out power is highly solar radiation dependent. Any prompt fluctuation in solar radiation will cause changes in output power variations. For instance, during sunrise the PV output power increases rapidly and considerably. There is a possibility of reaching the maximum power in short period depending on the rise change of the inverters. Additionally, the change may result from the weather conditions in the vicinity of PV plants.

Finally, the absence of system voltage and frequency, power quality is deteriorated. Also compared to synchronous generators, the PV installations have no issues related to reconnection because they do not need synchronization. Once a fault is detected at network node that is connected to both network and PV generation, the breaker from the network opens to solve the faults. The challenges associated to PV integration vary from one power system to another based on the PV input intensity compared to the power system and their respective topography.

2.2. Static Var Compensator (SVC)

2.2.1. Description of SVC

Static Var Compensator (SVC) belongs to the first-generation FACTS (Flexible AC Transmission Systems) devices used to control the power flows using power electronics in the power distribution networks. The SVC controls terminal voltage to monitor the quantity of reactive power injected into or consumed along the power system. When the voltage is high in the system, the SVC becomes capacitive and produces reactive power, on the contrast it becomes inductive i.e consumes reactive power [6]. The SVCs play a vital role in enhancing the system's performance, such as in voltage regulation, temporary stability progress, increasing transmission capacity, decreasing overvoltage provisionally, power actor as well as the harmonics among others. Fast response, extensive operational range and high reliability are the most characteristics of a Static Var Compensator device. Several methods showed that the thyristor valves are required practically together with capacitor and reactor banks to produce and regulate reactive power. The SVC's key function is controlling the voltage at desired bus while monitoring the reactive power injected at that particular point. It is very suitable to maintain or to keep the levels of esteemed voltage for functioning and using loads. In a simple system, the SVC contains a thyristor-controlled reactor, mounted alongside the bank of capacitors [8]. Contrary to synchronous condenser, SVC does not have moving component.

For AC network, the SVC acts as shunt-connected with changeable reactance that further produces or consumes the reactive power in demand to control the amount of the voltage at the connection point. It is widely use to deliver rapidly reactive power and voltage regulation sustenance. Practically due to the adjustment of thyristor's firing angle, the SVC has prompt rapidity of response.

The SVC's schematic design is shown as shunt-connected device in figure 1.1, comprising TCR and TSCs. The SVC is an automated device aimed at bringing the power factor of the system closer to unity [6]. Additionally, SVC experience parallel connection with line and central role is controlling the voltage at a particular bus by regulating its corresponding reactance.

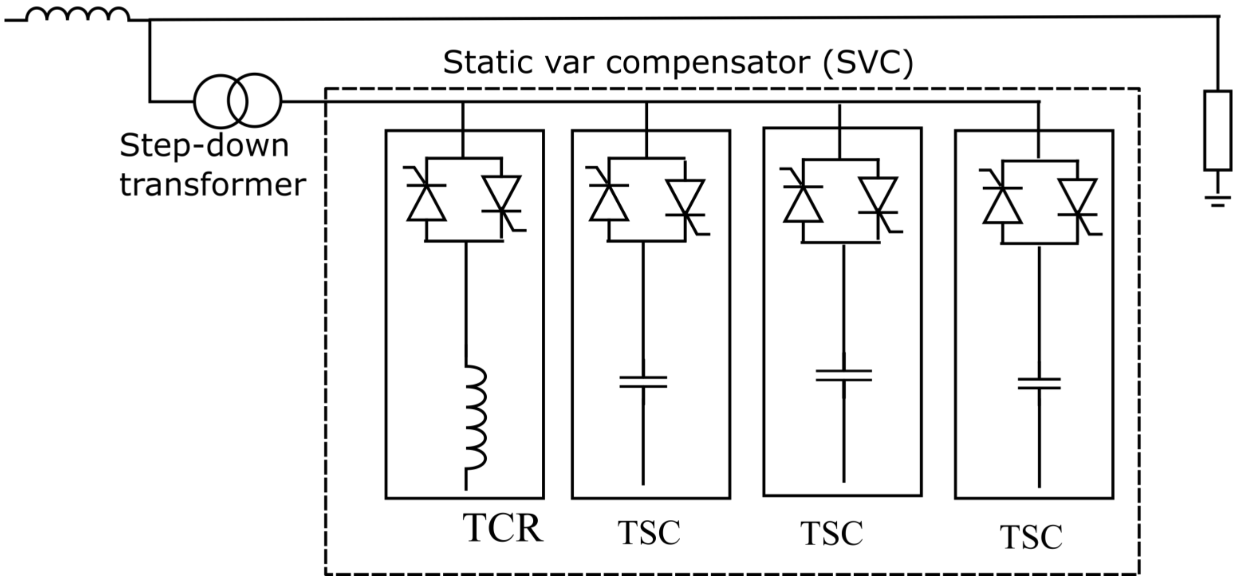

Figure 2.1 SVC of the TCR-TSC Type [9]

SVC regulates voltage at its terminals to control the quantity of reactive power introduced into or consumed from the power system. The SVC is called capacitive in other words generating the reactive power when system voltage is small; and once the voltage increases the SVC will act as reactive power absorber also known as SVC inductive. The reactive power change is achieved by switching three-phrase capacitor and inductor banks connected to the second side the transformer. The thyristor switches named also Thyristor Switched Capacitor (TSC) are used to turn on and off the capacitor. Reactors may be classified as Thyristor Switched Reactor (TSR) when on-off or Thyristor Controlled Reactor (TCR) when phase-controlled. Therefore, SVC compensates the voltage by absorbing or producing reactive power [10].

In this work, a technique of combining of TCR and TSCs was presented for controlling the grid connected photovoltaic system using the SVC controller, mainly three TSCs and one TCR as shown in fig.1.1.

Briefly, the core of SVC is, by compensating the reactive power, to sustain the voltage from a specific bus while modifying the thyristors' firing angle. SVCs may be categorized into two main groups based on their usage, i.e. Transmission SVC group when SVC's main role is to balance the transmission voltage and Industrial SVC group if it is used to enhance the power quality.

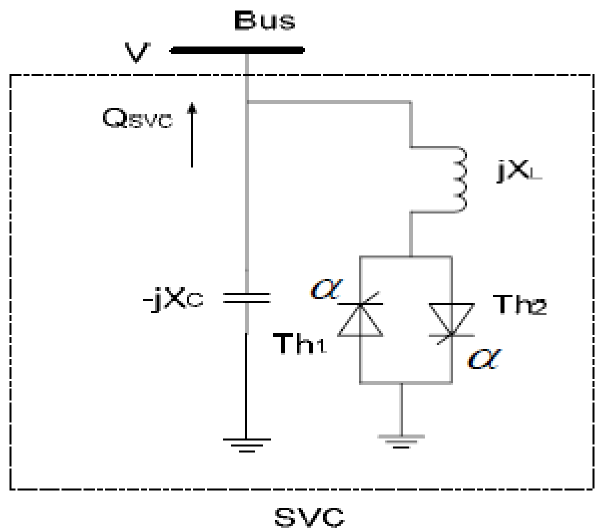

Figure 2.2 SVC firing angle mode [11]

An SVC as a device to recover power quality on electrical energy systems worldwide experiences the importance of the economic weight. So, a significant comprehension of structural control and active behavior of SVC is vital for a suitable compensator to use. This impartial could be accomplished through simulation using computer because it is very essential in the design and SVC's test as well as other devices. During dynamic modeling of the projected system, the simulation environment is achieved by using the MATLAB.

2.2.2. Previous Work on SVC in PV System

Various studies discussed the application of SVC in PV systems including both optimal operation and optimal placement for decades. Static VAR systems found their application in transmission for various reasons.

In 2014, Aleksanar and Zeljko carried out voltage analysis and propose generic solution in sizing and locating the SVC devices to enhance the voltage profile in PV and wind distribution network from Banat region in Serbia. In this study, SVC devices prove to be effective solution to the voltage variations in the network.

In 2018, an interesting case study from Maui island, Hawaii islands and USA (Riva Sanseverino, Tran, Leon, Staci, Thai, Doan and Nguyen, 2018) and proposed an optimal placement method of SVC for PV grid distribution while considering installed SVCs and voltage deviation from a referenced bus. The outcome of this study validates the benefits of the suggested method and the voltage regulation is achieved and voltage deviation improved.

In (Xu, Zhao, Xue and Jiayong, 2018) another study suggested a novel optimal SVC placement to maximize PV acceptability while minimizing the SVC investment cost and sustain the power quality and stability of the system. As results, the proposed approach was found effective on modified IEEE 37-bus model.

Briefly, the significance of SVCs in enhancing the functioning of PV grid-connected system increase as more solar energy sources are come online. Also, it is very clear that different studies confirmed the efficiency of using SVC in PV systems from different cases encountered in their works.

2.3. Research Gap

Since today, it is costly to implement the renewable energy sources while the electricity grid cannot handle the changeability. Presently, the entire contribution of all renewable to electricity generation comprises about 19%, a vast majority (83%) of it being depended of hydroelectric power [12]. To use solar PV for grid electrification, it is strongly suggested and justified. The present cost of PV devices still lesser than a decade ago, but to deliver power to complete the conventional electric supply is still too high. Due to the variation of power, it is a challenge to integrate the power generated by solar PV. The amount of solar that could be integrated into the power system has no major limitations. To improve and attain steadiness and competence of the connection, numerous research and investigation on renewable energy integration have stayed observed.

2.4. Problem Formulation

The corresponding objective function of the optimum SVC's location comprises voltage enhancement outline, a decrease of the system's real and reactive power losses. Power flow's equality limitations, bus's voltage limits as well as transmission line congestion capacity to determine the SVC's in best location along power systems are the most mutual constraints to be taken into consideration in this analysis. The SVC is shown as a variable reactive power connected to a bus in a system.

The reactive power generated by SVC is given by:

$$Q_{SVC}^{Min} \leq Q_{SVC} \leq Q_{SVC}^{Max} \quad (2.1)$$

Where, Q_{SVC} is defined as the injected reactive power (lagging or leading) at the bus where SVC is located.

To minimize the active power drop and voltage divergence is the purpose of improving the voltage steadiness under contingency situation by optimally locating the SVC as well as related considerations. The optimization problem aims at minimizing the changes in voltage and the active power losses. In particle swarm optimization, can be stated the objective function as follows;

$$\min f = P_{Loss} + \lambda VD \quad (2.2)$$

Where:

P_{Loss} = Network real power loss; VD = voltage deviation

λ is the penalty co-efficient to give equal weightage for losses and voltage deviation

At separately loaded bus the deviation of voltage has to be decreased. The voltage deviation (VD) function to be reduced is given by:

$$VD = \sum_{n=1}^{N_{PQ}} |V_m - V_{ref}| \quad (2.3)$$

Where:

V_m = The voltage magnitude at bus m; V_{ref} = referenced load bus voltage value set at 1; N_{PQ} = load bus's number.

The objective function to minimize the power loss is completed by choosing the finest mixture of variables, which decrease the loss in total real power of the system at the same time filling all the network constraints. It can be stated mathematically as follows:

$$P_{Loss} = \sum_{n=1}^{N_L} G_{mn} (V_m^2 + V_n^2 - 2V_m V_n \cos\delta_{mn}) \qquad (2.4)$$

Where:

V_m = The amount of voltage at m[th] bus; V_n= theamount of voltage at n[th] bus; G_{mn} = the line conductance between m-n buses; δ_{mn} = the angle between V_m and V_n; N_L= the sum of transmission lines.

Meanwhile, the smearing SVC's purpose is to regulate system parameters like real and reactive power in line flows and bus voltages, the next controls are taken into consideration. The equilibrium of active and reactive powers must be fulfilled in each node. The equality between the power generated by buses, the sum of load demand and sum of real power loss in the transmission lines must be fulfilled also. Power stability with respect to a bus can be expressed as:

$$P_{Gm} - P_{Dm} = \sum_{n=1}^{N_L} V_m V_n Y_{mn} X\cos\delta_{mn} + \gamma_n - \gamma_m = 0 \qquad (2.5)$$

$$Q_{Gm} - Q_{Dm} = \sum_{n=1}^{N_L} V_m V_n Y_{mn} X\sin\delta_{mn} + \gamma_n - \gamma_m = 0 \qquad (2.6)$$

Where:

P_{Gm} = The real power generated at m[th] bus; Q_{Gm} = the reactive power generated at m[th] bus; P_{Dm} = the real power demand at m[th] bus; Q_{Dm} = the reactive power demand at m[th] bus; Y_{mn} = the magnitude of bus admittance element m, n.

2.5. Chapter Conclusion

In order to decrease losses along transmission and distribution lines, rise flexibility of network, minor production expenses and decrease supplies to finance novel utility generation capacity integrating PV system into national grid. To predict the effect of PV inclusion and production on system steadiness, the use of progressive integration skills must be taken beforehand plant connection, to support the generation and distribution company. By producing or absorbing reactive power, a static var compensator is intended to expand the power system performance due to control/ adjust the voltage. Therefore, the fluctuating levels of power factor decreased when the load is changed and causes the improvement of constancy in the power system while the load is changed by using SVC in the power system.

CHAPTER 3

METHODOLOGY

3.0. Introduction

This chapter defines different technical adoptions and procedures of conducting this study. Specifically, discussion of previous methods applied to the problem, optimization tool used, simulation tool and the mapping method to the problem.

3.1. Previous Methods

Properties of renewable energy types give rise to various issues to micro-grid. To cite few issues, voltage flops, variations in voltage and frequency and faults related to phase difference in isolated and in network connected operation modes. The combination of renewable energy types and electricity network present disadvantages on the quality of the power especially connection and constancy issues. The optimization techniques are categorized into conventional methods, intelligent-based methods and mixed methods.

3.1.1. Conventional Methods

Some existing conventional optimization techniques are used in problems related to allocate and size the Distributed. The benefits of using analytical methodologies to tackle the optimization problems increased importantly.

a) Analytical Methodologies

A numerical equation is commonly considered to optimize a problem using Analytical methods. The correctness of this approach is highly subjected to the developed model. The approach requires another model to combine with depending on the results from the simulation of the system. These methodologies depend on the theory, calculus and mathematical analysis. For example, the tested analytical technique depended on the continuous analysis of power flow calculations as well as finding the prone buses to the voltage fall. This method showed to be effective in enhancing the voltage profile and decreasing the power losses whereas it gives rise to the amount of power transfer [13].

They provide a benefit of requiring short time as well as being easily implemented while confirming the problem convergence.

b) Fuzzy Logic (FL)

In 1979, the fuzzy logic method was introduced as a generality of classical theory to tackle power system related issues. The approach is mainly used to solve problems related to allocating and sizing of Distributed Generators. In [13] for example, this technique was applied to determine the optimum location of DGs and reducing the real power losses and improving the voltage profile.

3.1.2. Intelligent-Based Methods

In overall, the Artificial Intelligence approach is represented as the display of aptitude within machines. Heuristic techniques are regarded as intelligent-based approaches comprising algorithms that accelerate the procedures of determining an acceptable or near optimum answer. Compared to analytical approaches, heuristic method has major benefit of being easy. On the other hand, it gives low accuracy and precision [14].

a) Genetic Algorithm (GA)

Generic Algorithm is one of the heuristic approaches developed in the beginning of developing intelligence-based methods since 1975 and was introduced by Holland. This technique is described as a search technique mainly depending on the genetics and natural selection, like, selection, crossover, mutation, and inheritance. Based on the specification of selection rules, GA enables a population to change in a way that maximizes the "fitness" which in contrast to other search approaches that work on a single result. The genetic algorithm (GA) proved to be effective and beneficial in large search space and complex areas, as well as where it is difficult to find a solution like in a limited search space. This algorithm is usually applied in conditions which are not expressed in a specific mathematical model [15]. In the literature, GA is found to be the utmost used optimization method in dealing with problems related to locating and sizing DGs.

Advantages:

i) Easily being used simultaneously in discrete and continuous situations with technical constants;
ii) Can be used in complex and ambiguous problems;
iii) Final solution is not negatively affected by bad solutions;
iv) Do not require derivatives;
v) Have improved achievement at identifying the global optimal to a wide-ranging of functions.

Disadvantages:

i) Introduction of bad solutions.
ii) Can be trapped into local extreme.
iii) Time consuming when it comes to a large and complex problems due to repetition of evaluating fitness function.

b) Simulated Annealing (SA)

Simulated Annealing is another heuristic approach used in solving problems related to combinatorial optimization and it is iterative algorithm that exploiting crystallization procedure in a physical system commonly indiscrete search space. Firstly, the method is introduced in 1983 by Kirkpatrick et al., and it was later developed by Cerny in 1985. SA optimization technique found its central point in the cooling criterion. The required variables of SA method are temperature at initial stage (T), cooling change (β) as well as the end temperature (Tmin). A feasible solution point is initiated for the process. Once the system is disturbed, new possible solution is determined using probabilistic acceptance condition. By various authors, SA is used in locating and defining the size of DGs at the same time decreasing the required time for computing compared to Generic Algorithm and Tabu Search approaches. Additionally, SA approach is preferable to optimize problems depending on required reliability criteria [14].

Advantages:

i) Simplicity for implementation;

ii) Can give acceptable answers to various combinatorial problems;

iii) Being robust.

Disadvantages:

i) May end in a local minimum;

ii) Have huge computing time;

iii) Cannot give information on the magnitude by which the local minimum deviates from the global minimum;

iv) No guide on the choice of local minimum for the initial configuration;

v) Cannot provide an upper limit for the computation time.

c) Tabu Search (TS)

Tabu Search method is a meta-heuristic technique introduced by F. Glover in 1986 for solving optimization problems. The technique depends on the adaptive memory and responsive exploration principle that enabling to find the solution space in a cost-effective manner until no improvement is achieved. TS were highly identified in solving the locating and sizing of DGs problem. However, TS has the disadvantage of large number of iterations and parameters to be determined.

Advantages:

i) Useful for composite problems;

ii) Take a clear memory;

iii) Used for discrete and continuous variables;

iv) Used for big problems.

Disadvantages:

i) Subject to the tactic for Tabu list guidance;

ii) Get stuck in local minima;

iii) Define numerous restrictions;

iv) Much iterations;
v) Subject to parameter settings to determine global optimum.

3.1.3. Hybrid Heuristic Methods

To improve the quality of the solutions and simplify the implementation, researchers are accepting new approaches on continuous basis and combining old techniques. The resulted methods are called hybrid approaches, methods or techniques [13].

3.2. Particle Swarm Optimization

The word “Particle” represents a bird in a flock or bee in a group.” Swarm” represents the moving particles with a certain velocity. ” Optimization” is defined as the process of finding the best solution to a given conditions or situations. In other words, PSO is a global optimization method based on population enabling an amount of distinct solutions, also called particles, moving in a hyper dimensional search space searching the best. Each particle is characterized by a position and a velocity vectors, which are iteratively adjusted by learning from a local best found by the particle itself and a current global best found by the completely moving particles [14].

3.2.1. Background of Particle Swarm Optimization

In 1995, Eberhart and Kennedy introduced a new optimization method named Particle Swarm Optimization (PSO).The inspiration of this method come from the social behavior of bird grouping and fish schooling (the individuals are moving in a multidimensional search space, where single intersection of all dimensions forms an individual). Firstly, the system is modified by an arbitrary set of solutions and the optimization process is ensured through the generation updates. At every single iteration, the particle’s position is assessed considering their suitability level, and in order to improve the final solution the neighboring individuals show the history of their “best” positions [10]. As an example given, PSO is useful in the selection of the optimal location, type, as well as the size of DG units to succeed in the optimal integration of DGs considering the harmonic limitations and protection restrictions [13].

3.2.2. Discussion of PSO

The particle swarm algorithm is initialized with a population of arbitrary solutions and tries to give an optimum answer updated at each iteration. The initial requirements of the approach considered as vital parameters include iteration number, swarm quantity, correction factor and inertia moment. In this technique, the individuals change their positions until the number of iterations is achieved. Therefore, every particle profits from the experience of not only the best particle in the group, but also all other moving particles [15]. In addition, a PSO was working to improve the voltage profile, to decrease losses, and costs, etc. It is showed that the PSO provided improved answer quality and a lesser quantity of iterations compared to Genetic Algorithm (GA) technique [13]. Few advantages and disadvantages of the PSO are presented below:

Benefits:

i) Simplicity during its implementation;
ii) Few constraints to modify;
iii) Possibility to run parallel computation;
iv) Being robust;
v) Have higher chance and effectiveness to find the global optima;
vi) Fast to meet the convergence criteria;
vii) Not overlap and mutate;
viii) Short computational time;
ix) Efficient in solving problems with difficulty in find mathematical models accurately.

Disadvantages:

i) Not easy to initialize the design parameters,
ii) Presents difficulty in scattered problems,
iii) Experiencing too early convergence and be trapped into a local minimum especially for composite problems.

Briefly, the optimization algorithms are used in controlling the voltage and limiting the current for temporary steadiness in alternating current or direct current micro-grids including photovoltaic energy, wind turbines, fuel cells, battery energy storage systems as well as flywheel energy storage whereas working in the isolated mode such as genetic, particle swarm and artificial bee group algorithms among others [15].

3.2.3. Mapping Method to the Problem

In a Particle Swarm Optimization system, the individuals move in a complex search space. Every particle regulates its individual position and based on the knowledge of the nearest particle, utilizes the finest location came across by itself and its nearest, during flight [16]. The formulation of an objective optimization problem is completed considering the two main sub-functions to minimize the voltage changes and power losses and is subjected to limits. The main objective function is written as follow:

$$f = P_{Loss} + \lambda VD \qquad (3.1)$$

Where P_{Loss} denotes the real power loss of the system; VDdenotes the voltage deviation.

The same objective function is considered in defining the optimum values of SVC device.

Mathematical model of Static Var Compensator: It is defined as a shunt-connected static var producer or consumer whose output is attuned to argument capacitive or inductive current thus keep and regulate exact the electrical power system factors (typically bus voltage). It is demonstrated as an ideal injected reactive power at the load ends [16].

The SVC current is expressed in Eq. 3.2:

$$I_{SVC} = jB_{SVC} V_k \qquad (3.2)$$

The SVC reactive power, which is also the injected reactive power at k^{th} bus, is drawn in Eq. 3.3:

$$Q_{SVC} = Q_k = -V_{k^2} B_{SVC} \qquad (3.3)$$

Where:

B_{SVC} = the SVC's susceptance; V_k = the voltage of k^{th} bus.

Mathematical model of Particle Swarm Optimization: The moving of individuals (particles) reset with a group (population) of arbitrary candidate solution change through the problem of d-dimension space to hunt the novel answers. The suitable position, pbest, is calculated. Respectively, each individual has its own location and speed. The suitable (best) location amongst the swarms, gbest, is updated in every iteration [17]. Their respective location and speed are updated following equations:

$$V_k^{n+1} = W_k V_k^n + C_1 \times rand_1 \times (pbest_k - S_k^n) + C_2 \times rand_2 \times (gbest_k - S_k^n) \quad (3.4)$$

Where,

$$S_k^{n+1} = S_k^n + V_k^{n+1} \quad (3.5)$$

$$W = W_{max} - \frac{W_{max} - W_{min}}{iterw_{max}} \times iter \quad (3.6)$$

V_k^n= the velocity of k[th] particle at n[th] iteration; V_k^{n+1}= Velocity of k[th] particle at (n+1)[th] iteration; S_k^n= Present location of particle k at n[th] iteration; S_k^{n+1}= Present location of particle k at (n+1)[th] iteration; $pbest_k$= individual suitable position of k[th] particle; $gbest_k$ = Best global position of swarm (entire group of the particles); C_1=the self-recognition component coefficient; C_2 = the social component coefficient; $C_1 + C_2$= 4 $rand_1$ and $rand_2$ are the random numbers commonly chosen between 0 and 1;W = Inertia weight; W_{max} = Maximum value of inertia weight; W_{min} = Minimum value of inertia weight; iter = Present iteration; $iter_{Wmax}$ = Maximum iteration.

Real Power Loss

The achievement of the minimum value of the real power loss is facilitated by the best parameters minimizing the sum of real power loss of the system and fulfilling all the boundaries. Mathematically, the real power loss equation is given by:

$$P_{Loss} = \sum_{n=1}^{N_L} G_{mn} (V_m^2 + V_n^2 - 2V_m V_n \cos\delta_{mn}) \quad (3.7)$$

Voltage deviation

Improvement of the system's voltage is achieved by minimizing the voltage changes at every load bus as much as is achievable. The minimized voltage changes function can be expressed as:

$$VD = \sum_{n=1}^{N_{PQ}} |V_m - V_{ref}| \quad (3.8)$$

Where:

V_m = The voltage magnitude at bus m; V_{ref} = the referenced voltage value and is equal to 1; N_{PQ} = load bus number.

Optimization Constraints

The objective function depends on a number of limits and the solutions must be maintained within these limits. Among the constraints considered during this optimization process, include voltage and power loss limits, SVC ranges.

a) The SVC inequality is expressed as follow:

$$Q_{SVC}^{Min} \le Q_{SVC} \le Q_{SVC}^{Max} \quad (3.9)$$

Where, Q_{SVC} is the injected reactive power (lagging or leading) into the bus holding the SVC.

b) The voltage magnitude inequality is expressed as follow:

$$V_i^{min} \le V_i \le V_i^{max} \quad (3.10)$$

c) The power equalities are given as follow:

$$P_{Gm} - P_{Dm} = \sum_{n=1}^{N_L} V_m V_n Y_{mn} X\cos\delta_{mn} + \gamma_n - \gamma_m = 0 \quad (3.11)$$

$$Q_{Gm} - Q_{Dm} = \sum_{n=1}^{N_L} V_m V_n Y_{mn} X\sin\delta_{mn} + \gamma_n - \gamma_m = 0 \quad (3.12)$$

Where P_{Gm} is The real power generation at bus m; Q_{Gm} is thegenerated reactive power at m^{th} bus; P_{Dm} is the real power demand at m^{th} bus; Q_{Dm} is the reactive power demand at m^{th} bus; Y_{mn} is the magnitude of bus admittance element m, n.

3.3. MATLAB

It is influential and multipurpose simulation software, generally used in industry and academia. It is suitable for mathematical matrix manipulations for designing numerical analysis of linear control systems. It earns time to develop its language and convert with numerous procedures wanted for basic simulations and the main disadvantages of this program are its scope and relative complication. For inexperienced users the equations must be touched in certain method and arrangement, needful the user to be familiar with the phenomena being examined, assembly it somewhat complex.

To validate the mentioned approach, the simulation exercises are placed in Matlab, the PSO algorithm is applied for best position of SVC using Matlab as simulation tool. This thesis pursues an application of the Static Var Compensator to balance the voltage of the power system through the Matlab as the simulation environment.

3.4. Chapter Conclusion

To explore the effect of SVC on power systems the proper SVC model is a vital. In this unit, SVC and its mathematical model were presented and the optimization function and its constraints were discussed. Quickly, the SVC takes the capability to consume or add the reactive power through public network. This work, it is an operative technique to develop the electricity by connecting generated solar power and controlled and steadied voltage supported by installation of a Static VAR Compensator.

CHAPTER 4
RESULTS AND ANALYSIS

4.0. Introduction

In this chapter, the obtained results using Particle Swarm Optimization approach are presented and discussed. The optimum location and rating of SVC device for minimizing the objective function using PSO algorithm are determined successfully. The findings are mainly grouped in two groups based on the voltage improvement and power losses reduction. The PSO algorithm is tested on IEEE 14 bus system. This network comprises five (5) generators with one of them being slack and 20 lines. The Table 4.1 illustrates the considered variables for PSO technique. The PSO algorithm was implemented in MATLAB 2021a environment. The code used in this study and data are given in Appendix. In order to optimize the SVC, the equality constraints and inequality constraints should be considered. Therefore, the amount of voltage values, generated real power, generated reactive power at all buses, transformers 'tap position, the line power flows, and reactive power of SVC are kept within the constraints limits. The Table 4.1 summarizes the limits of PSO parameters during the implementation of the technique.

Table 4-1.PSO Parameters

Parameters	**Optimal value**
Population	50
Number of iteration	100
Initial weight (W_{min})	0.4
End Weight (W_{max})	0.9
baseMVA	100
C1	2.5
C2	1.5
Voltage limits	
Low voltage limit	0.95
Upper voltage limit	1.1

4.1. Results and Analysis

The load of the IEEE-14 system is 259 MW in total, 73.5 MVAR and slack bus 1 is bus number one (1). The voltage and angle values of the system without SVC are summarized in Table 4.2.

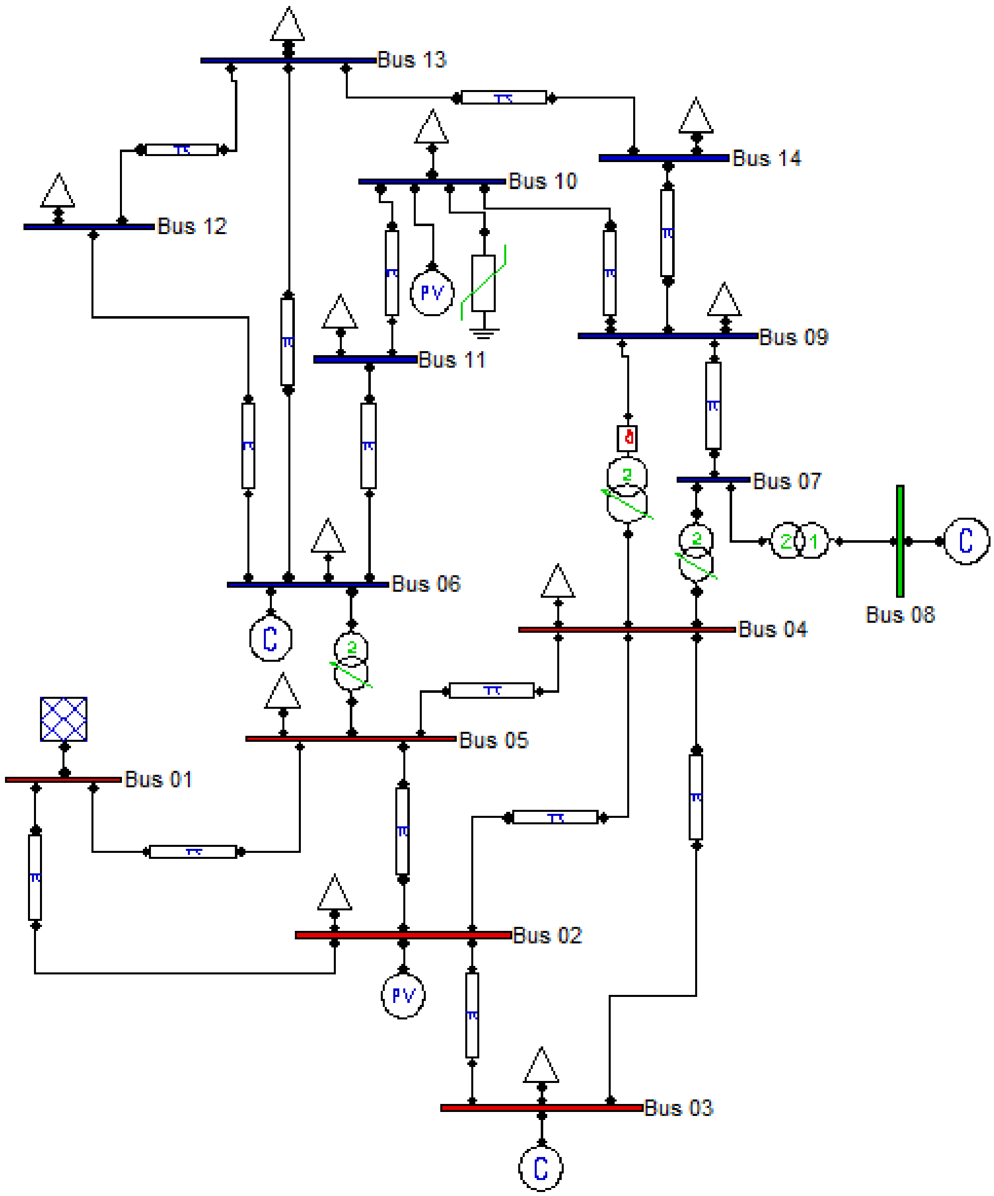

Figure 4.1. IEEE 14 Bus-System with SVC

Table 4-2.The voltage and angle values of the system without SVC

Bus no.	Voltage Magnitude (p.u)	Angle(degree)
1	1.06	0
2	1.045	-4.9874
3	1.01	-12.7424
4	1.0142	-10.2564
5	1.0172	-8.7646
6	1.07	-14.4177
7	1.0503	-13.2519
8	1.09	-13.2519
9	1.0337	-14.8323
10	1.0326	-15.0412
11	1.0475	-14.8478
12	1.0535	-15.2684
13	1.0471	-15.3081
14	1.0213	-16.0647

The location and size of SVC are initialized and optimum function is calculated at each particle and the voltage and power losses are minimized. SVC's optimum location is identified at the first bus with a capacity of 0.149p.u. After installing the SVC at Bus 1, the voltage profile is improved and the power losses decreased. The SVC's optimal values for IEEE-14 bus using PSO approach are presented in table 4-3.

Table 4-3.Optimum location and size of SVC using PSO for IEEE-14 Bus System

	Location	**Susceptance rating (p.u)**
PSO	Bus 1	0.149

4.1.1. Voltage Improvement

The Figure 4.2 illustrates the SVC result on voltage improvement. The voltage profiles before and after SVC optimization is compared and it is observed that the installation of the SVC (in red line) improved the voltage profile of the system compared to the base situation deprived of SVC (in black).

A remarkable voltage improvement is observed at the bus no. 1(increase of 0.041p.u) followed by bus no. 3 (an increase of 0.036p.u). A decrease of 0.04p.u, 0.039p.u and 0.038p.u in the voltage magnitudes is observed at bus 6, 12 and 13 respectively. The placement of the SVC at bus 1with reactive power injection of 14.9 MVAR and reduced the losses significantly (Fig. 4.2) improved the voltage profile. The figure obviously shows that the buses voltages are in set of bounds at smallest active power loss with SVC at optimum position.

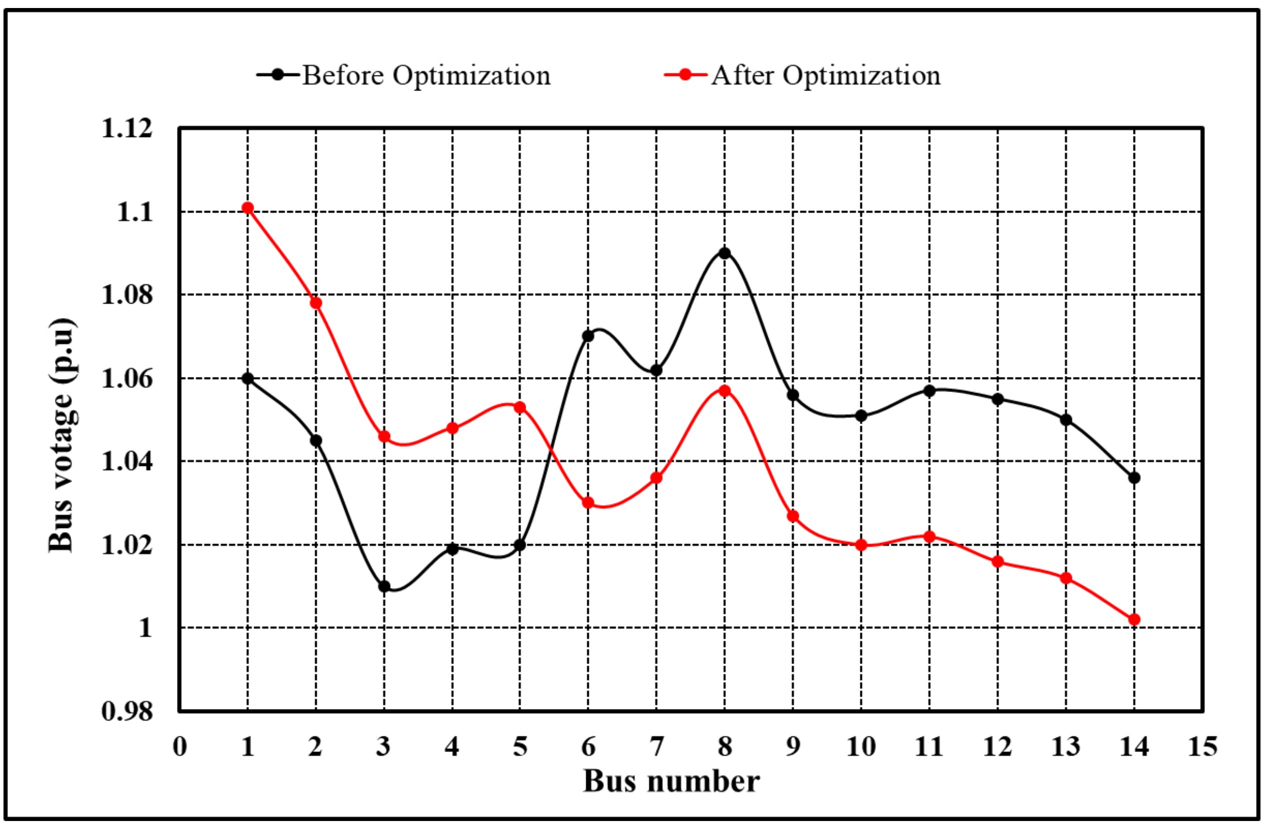

Figure 4.2 Comparison of voltage profiles improvement before and after optimization process

4.1.2. Power Losses Reduction

The convergence characteristic of the PSO algorithm is presented in Figure 4.3, which show the impact of SVC on the power system losses. It is very important to note that optimization of the SVC reduced significantly the power system losses. A decrease of 1.27MW is noted in the reduction of real power loss i.e falling from 13.54MW to 12.27MW. The power losses reduction is achieved.

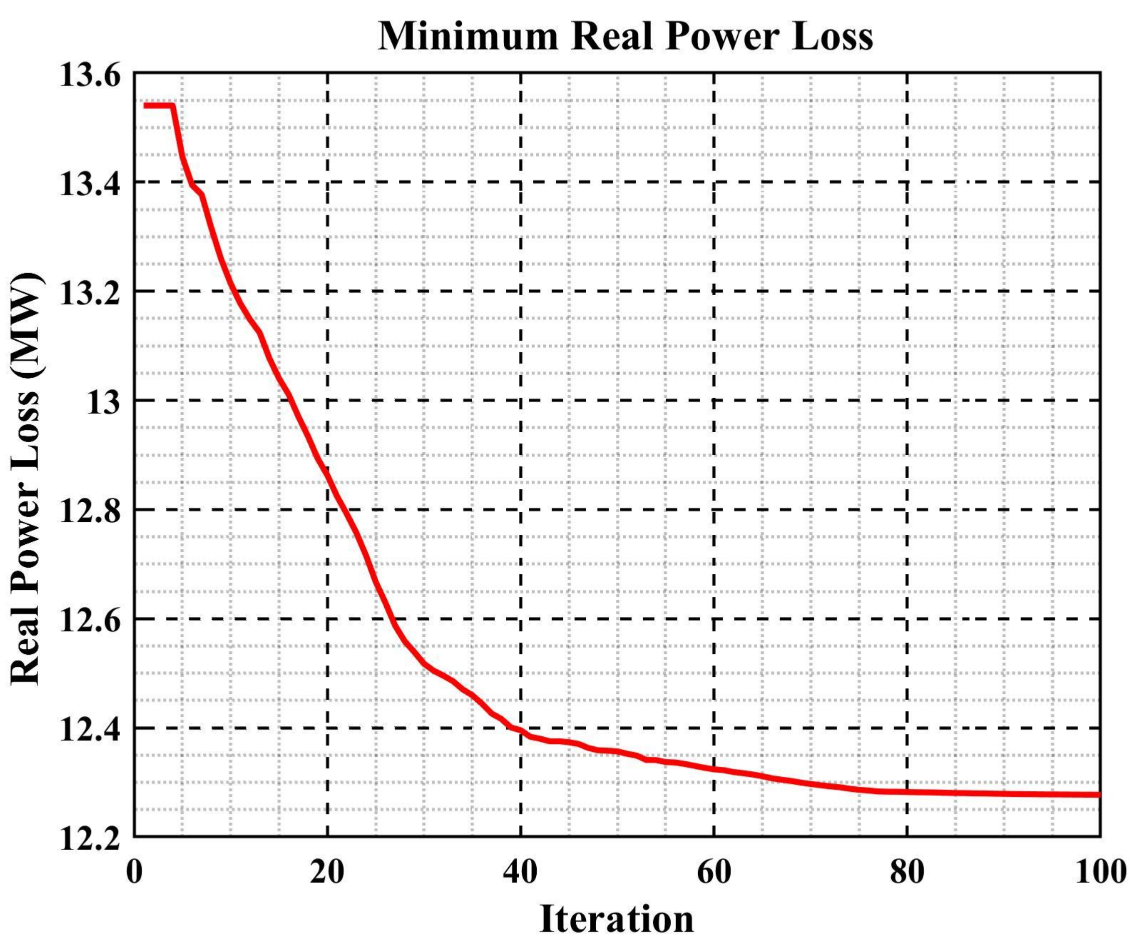

Figure 4.3 The real power loss of the system versus iteration number

Figure 4.4 displays the bus reactive power generations at the least reactive power loss with SVC at the optimal location. The orange bars represent the generations at minimum reactive power loss by means of SVC while the blue bars shows the base state deprived of SVC.

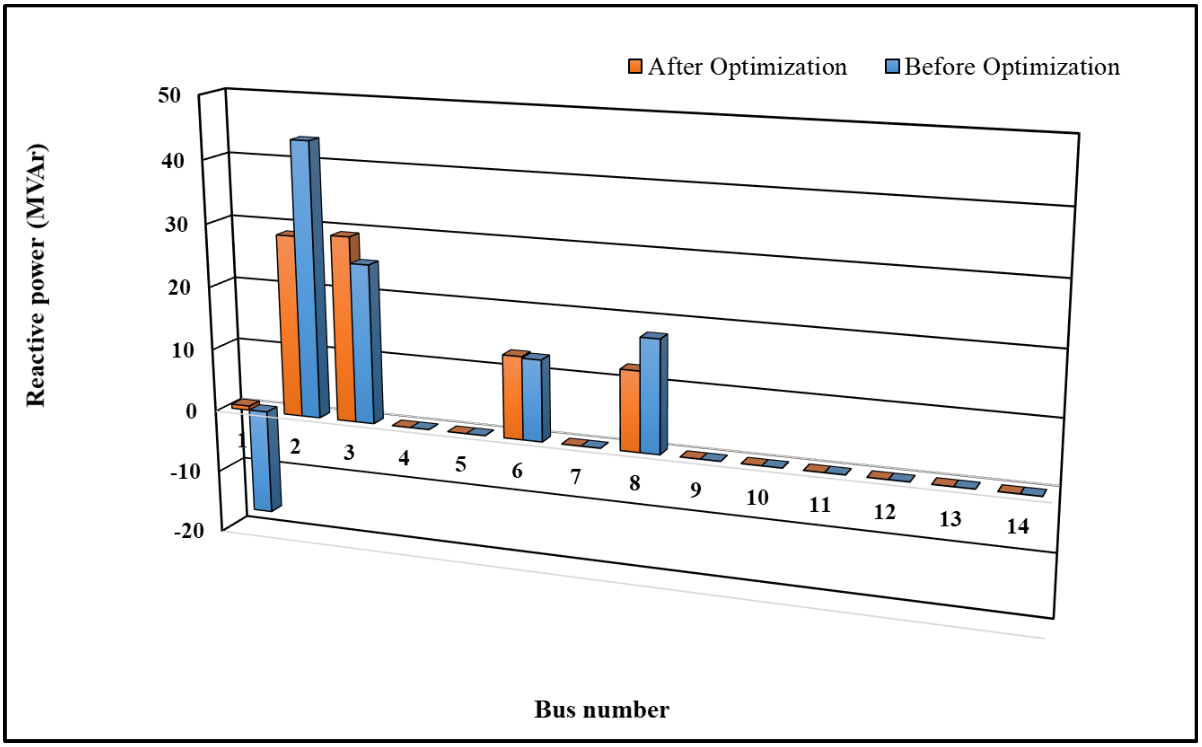

Figure 4.4 Reactive power generation of the system

4.2. Validation

In 2008, Metwally et al. [18] found voltage profile improvement when the SVC is connected to bus 5 with a rate of 51.66 MVAR using Genetic Algorithms. In 2016, Kavitha and Neela [19] obtained the optimum locations of SVC to be 11 and 13 buses with ratings ranging from 10.663MVAR to 24.43MVAR using PSO technique depending on the load ability factor.

Recently, Ismail et al. (2021) in [20] found that the optimum position of Static Synchronous Compensator (STATCOM) in IEEE-14 bus system be at bus number 7 using NEPLAN software.

SVC is a shunt-connected controller able of all possible profit of FACTS devices. In addition, it is simple to integrate in load flow result and extremely fit for VAR support. After installation of SVC, a remarkable power loss reduction is noticed and the voltage profile was also enhanced. A notable voltage improvement is observed at the bus no. 1(increase of 0.041 p.u) followed by bus no. 3 (an increase of 0.036 p.u). A decrease of 0.04p.u; 0.039p.u and 0.038p.u in the voltage magnitudes is observed at bus6, 12 and 13 respectively and a decrease of 1.27MW is noted in real power loss i.e from 13.54 MW to 12.27 MW.

4.3. Chapter Conclusion

Particle Swarm Optimization approach is applied on the IEEE-14 bus system. The algorithm determined successfully the optimum place and capacity of SVC. The assigned settings of the PSO parameters proved to be the best. The voltage profile and active power losses of the system by optimally located SVC device were discussed. The obtained results are found encouraging after being applied on the IEEE-14 bus system.

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

5.1. Conclusions

To conclude, this study showed the PSO algorithm formulation and implementation to reduce system the power loss as well as enhance the voltage profile by optimizing the place and capacity of Static Var Compensator in the PV-grid system. In this study, changes in voltage and power loss were considered for the objective function to enhance the voltage balance of the system. IEEE-14 bus system is used in validation of the technique. This network comprised five (5) generators and twenty (20) transmission lines. The best place and size of SVC were calculated.

The proposed algorithm located the SVC at the bus no. 1 as the optimal location and optimal capacity of 14.9MVAR. After installation of SVC, a remarkable reduction in terms of power loss is noticed. The system voltage profile was also enhanced with the highest 1.01p.u and the lowest of 1.002p.u from this case. Therefore, the aims of the research work were successfully attained and the PSO technique proved to be a suitable approach to optimize the place and capacity of the SVC in power networks leading to the improvement of the network voltage profile and reducing real and reactive power losses in the system.

5.2. Contributions to Power Electronics with Solar Energy Integration

The utilization of energy is growing at a remarkable rate and more likely will continue to rise worldwide. The foremost of energy source is still fossil fuel leading to global warming problems because of greenhouse gases from the burnings of such fuel. Advancement in the power electronic presents high dependability and the efficiency of converting renewable energy, therefore supporting the energy conservation, enhancing energy efficiency, as well as serving in diminishing the dangerous emissions globally. Integration of new power electronics technology and intelligent control policies makes Renewable Energy resources further convenient as well as dynamic as the conventional power plants. There is will more development in power electronics domain for RESs enabling an improved and flexible integration with the grid. To provide reactive power compensation, shunt compensation can be used for this purpose; therefore FACTS controllers can be introduced. In this work, SVC as a parallel connected device of the Flexible AC Transmission Systems (FACTS) is used to improve the power system voltage stability. The absence of reactive power stretches positively to voltage instability, particularly once generators reach their bounds of reactive power production. Therefore, suitable compensation recovers and regulates voltage stability.

5.3. Recommendations

5.3.1. Adopting Research Thesis Findings

This study work will contribute to distribution companies both directly and indirectly. This research work will help the distribution companies to reduce penalties, minimize the compensation and increase their profit margins via reduction of the real and reactive power losses inside the networks. In addition, this research will help to integrate green energy sources to the networks easily. The research work will also ensure that they improve the voltage levels at the consumers to the required limits. Finally, this work will be beneficial for the customers, as their machines will be operating under stable voltage and to the country in general.

5.3.2. Recommendation for Further Work

The PSO programming code in MATLAB 2021a took long time for execution due to iteration, therefore additional works are recommended to reduce the time and make more efficient the algorithm. Addition to this, improvement of the objective function can be achieved by considering other power quality parameters such as power factor, line overloading, flicker and harmonics among others.

Further studies are also recommended on large power systems and through additional types of FACTS devices. Comparison of these results and the other optimization techniques' results are recommended.

In the future works, the proposed algorithm and objective function can be extended to existing power system and other IEEE systems with other kind of FACTS and other optimization methods.

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APPENDICES

A1: Coding List

```
%%%%%%%%%%% STATIC VAR OPTIMAL SIZE AND LOCATION %%%%%%%%%%%
%%%%%%%%%%%%%% Initialization %%%%%%%%%%%%%%
%Iteration=100, Swarm size=50
tic
clc
clear all;
close all;
iter=0;
iteration=100;
particlenumber=50;
%Inertia Weight
w_max=0.9;
w_min=0.4;
w_temp=w_max;
w_step=(w_max-w_min)/iteration;
%Voltage Maximum and minimum limit
vol_min=0.95;
vol_max=1.10;
%Load IEEE 14 bus data
[baseMVA, bus, gen, branch]=loadcase(case14);
%Initialization of Swarm & velocity
%Control variables: vg1 (1.06), vg2 (1.045), vg3 (1.01), vg6 (1.07), vg8(1.09)
%Control variables: tp1(4-7 0.978), tp2(4-9 0.969), tp3(5-6 0.932)
%Control variables: shunt9(19)
%Random 50*9 matrix
Swarm=[unifrnd(0.95,1.10,particlenumber,5), ...
unifrnd(0.975,1.025,particlenumber,3),unifrnd(0,20,particlenumber,1)];
%Initial velocity is set to 0
Velocity=zeros(particlenumber,9);
fori=1:particlenumber
 v1=Swarm(i,1); %v1
bus(1,8)=v1; %Vm, 8 is voltage magnitude (p.u.)
gen(1,6)=v1; %Vg, 6 is voltage magnitude setpoint (p.u.)
 v2=Swarm(i,2); %v2
bus(2,8)=v2;
gen(2,6)=v2;
 v3=Swarm(i,3); %v3
bus(3,8)=v3;
gen(3,6)=v3;
 v6=Swarm(i,4); %v6
bus(6,8)=v6;
gen(4,6)=v6;
 v8=Swarm(i,5); %v8
bus(8,8)=v8;
gen(5,6)=v8;
branch(8,9)=Swarm(i,6); %tp1 4-7, 9 is tap position
```

```
branch(9,9)=Swarm(i,7); %tp2 4-9
branch(10,9)=Swarm(i,8); %tp3 5-6
bus(9,6)=Swarm(i,9); %Shunt capacitor 9, 6 is BS

eval(['savecase ("case14_test' num2str(i) '.mat", baseMVA, bus, gen, branch)']);
eval(['results',num2str(i),'=runpf("case14_test', num2str(i) '.mat")']);
eval(['losses',num2str(i),'=sum(real(get_losses(results',num2str(i),')))']);
%Penalty for bus voltage violation
bus_inf=bus(:,8);
forbus_num=1:14
ifbus_inf(bus_num)>vol_max
penalty_bus(bus_num)=10000*(bus_inf(bus_num)-vol_max)^2;
elseifbus_inf(bus_num)<vol_min
penalty_bus(bus_num)=10000*(bus_inf(bus_num)-vol_min)^2;
else
penalty_bus(bus_num)=0;
end
end
penalty_bus_violation=sum(penalty_bus);
%Penalty for reactive generation violation
gen_inf=gen(:,3);
forgen_num=2:5
ifgen_inf(gen_num)>gen(gen_num,4)
penalty_gen(gen_num)=1000*(gen_inf(gen_num)-gen(gen_num,4))^2;
elseifgen_inf(gen_num)<gen(gen_num,5)
penalty_gen(gen_num)=1000*(gen_inf(gen_num)-gen(gen_num,5))^2;
else
penalty_gen(gen_num)=0;
end
end
penalty_gen_violation=sum(penalty_gen);
%Penalty for tap position violation
brch_inf=[branch(8,9); branch(9,9); branch(10,9)];
forbrch_num=1:3
ifbrch_inf(brch_num)>1.025
penalty_brch(brch_num)=10000*(brch_inf(brch_num)-1.025)^2;
elseifbrch_inf(brch_num)<0.975
penalty_brch(brch_num)=10000*(brch_inf(brch_num)-0.975)^2;
else
penalty_brch(brch_num)=0;
end
end
penalty_brch_violation=sum(penalty_brch);

%Penalty function
losses(i)=eval(['losses',num2str(i)]);

Obj_fun_initial(i)=losses(i)+penalty_bus_violation+penalty_gen_violation+penalty_brch_violation;
end
%%%%%%%%%%%%% Initialize Pbest and Gbest %%%%%%%%%%%%%
for j=1:particlenumber
Pbest(j,:)=Swarm(j,:);
Val_Pbest(j)=Obj_fun_initial(j);
end
```

```
[Val_Gbest,m]=min(3.178*Val_Pbest);
Gbest=Swarm(m,:);
Gbest_calc=repmat(Swarm(m,:),particlenumber,1);
%%%%%%%%%%%%%%%%% PSO %%%%%%%%%%%%%%%%%%%
losses_temp=zeros(1,particlenumber);
figure('NumberTitle', 'off', 'Name', 'Minimum Real Power Loss');
title('Minimum Real Power Loss');
ylabel('Real Power Loss (MW)');
xlabel('Iteration');
grid on;
hold on
foriter=1:iteration
    R1=rand(particlenumber,9);
 R2=rand(particlenumber,9);
%2.5+1.5=4;
 %2/abs(2-4-sqrt(4*4-4*4))=1
 Velocity=1*(w_temp*Velocity+2.5*R1.*(Pbest-Swarm)+1.5*R2.*(Gbest-Swarm));

% Set maximum velocity
forv_iter=1:9
ifv_iter==9
 Outstep=Velocity(:,v_iter)>0.1;
Velocity(find(Outstep),v_iter)=0.1;
 Outstep=Velocity(:,v_iter)<-0.1;
Velocity(find(Outstep),v_iter)=-0.1;
else
 Outstep=Velocity(:,v_iter)>0.003;
Velocity(find(Outstep),v_iter)=0.003;
 Outstep=Velocity(:,v_iter)<-0.003;
Velocity(find(Outstep),v_iter)=-0.003;
end
end
 Swarm=Swarm+Velocity;

for k=1:particlenumber
 v1=Swarm(k,1); %v1
bus(1,8)=v1; %Vm, 8 is voltage magnitude (p.u.)
gen(1,6)=v1; %Vg, 6 is voltage magnitude setpoint (p.u.)
 v2=Swarm(k,2); %v2
bus(2,8)=v2;
gen(2,6)=v2;
 v3=Swarm(k,3); %v3
bus(3,8)=v3;
gen(3,6)=v3;
 v6=Swarm(k,4); %v6
bus(6,8)=v6;
gen(4,6)=v6;
 v8=Swarm(k,5); %v8
bus(8,8)=v8;
gen(5,6)=v8;
branch(8,9)=Swarm(k,6); %tp1 4-7, 9 is tap position
branch(9,9)=Swarm(k,7); %tp2 4-9
branch(10,9)=Swarm(k,8); %tp3 5-6
bus(9,6)=Swarm(k,9); %Shunt capacitor 10, 6 is BS
```

```
eval(['savecase ("case14_test' num2str(k) '.mat", baseMVA, bus, gen, branch)']);
eval(['results',num2str(k),'=runpf("case14_test', num2str(k) '.mat")']);
eval(['losses',num2str(k),'=sum(real(get_losses(results',num2str(k),')))']);
%Penalty for bus voltage violation
bus_inf=bus(:,8);
forbus_num=1:14
ifbus_inf(bus_num)>vol_max
penalty_bus(bus_num)=10000*(bus_inf(bus_num)-vol_max)^2;
elseifbus_inf(bus_num)<vol_min
penalty_bus(bus_num)=10000*(bus_inf(bus_num)-vol_min)^2;
else
penalty_bus(bus_num)=0;
end
end
penalty_bus_violation=sum(penalty_bus);

%Penalty for reactive generation violation
gen_inf=gen(:,3);
forgen_num=2:5
ifgen_inf(gen_num)>gen(gen_num,4)
penalty_gen(gen_num)=1000*(gen_inf(gen_num)-gen(gen_num,4))^2;
elseifgen_inf(gen_num)<gen(gen_num,5)
penalty_gen(gen_num)=1000*(gen_inf(gen_num)-gen(gen_num,5))^2;
else
penalty_gen(gen_num)=0;
end
end
penalty_gen_violation=sum(penalty_gen);

%Penalty for tap position violation
brch_inf=[branch(8,9); branch(9,9); branch(10,9)];
forbrch_num=1:3
ifbrch_inf(brch_num)>1.025
penalty_brch(brch_num)=10000*(brch_inf(brch_num)-1.025)^2;
elseifbrch_inf(brch_num)<0.975
penalty_brch(brch_num)=10000*(brch_inf(brch_num)-0.975)^2;
else
penalty_brch(brch_num)=0;
end
end
penalty_brch_violation=sum(penalty_brch);

%Penalty function
losses_temp(k)=eval(['losses',num2str(k)]);

Obj_fun_temp(k)=losses_temp(k)+penalty_bus_violation+penalty_gen_violation+penalty_brch_violation;

ifObj_fun_temp(k)<Val_Pbest(k)
losses(k)=losses_temp(k);
Val_Pbest(k)=Obj_fun_temp(k);
Pbest(k,:)=Swarm(k,:);
end
end
```

```
 [Val_Gbest_temp,n]=min(Val_Pbest);
ifVal_Gbest_temp<Val_Gbest
Val_Gbest=Val_Gbest_temp;
Gbest=Swarm(n,:);
Gbest_calc=repmat(Swarm(n,:),particlenumber,1);
end
w_temp=w_temp-w_step;
Val_Gbest_rec(iter)=Val_Gbest;
plot(Val_Gbest_rec);
drawnow;

end
toc
```

A2: IEEE PES Power Africa Paper 2021

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Design of Static Var Compensator (SVC) for Improving Power Supply of Solar Energy Connected to the Grid

Marie Grâce Berwa
African Centre of Excellence in Energy for Sustainable Development
University of Rwanda
Kigali, Rwanda
berwamariegrace@gmail.com

Peter Musau Moses
Department of Electrical and Information Engineering
University of Nairobi
Nairobi, Kenya
pemosmusa@uonbi.ac.ke

***Abstract*—Development of renewable energy technologies has increased worldwide. Power systems, underneath intensely loaded situations, are at ultra-hazards of credible line outage and consequent voltage unreliability problem. Real power drop and voltage divergence minimization are measures of voltage security of power system grids. The work recommends the optimal usage of the SVC in the enhancement of the voltage stability. Promoting renewable energies has benefits not only for the environment but also for the economic conditions of the country. The challenging of voltage collapse has been expressed as an optimization problem based on the process of particle swarm optimization (PSO), applied in the study of voltage stability of a power system. The success of the projected algorithm confirmed in IEEE-14 Bus standard test system.**

***Index Terms*—Power System, Voltage Stability, Particle Swarm Optimization (PSO), SVC.**

I. INTRODUCTION

Nowadays, the world is developing energy sources other than fuel fossil and gas to mitigate the global warming that is affecting health of the population, the cloud weather, water pollution, animals as well as vegetation. The photovoltaic (PV) energy is an attractive renewable energy with an abundance in sunlight worldwide and its use has increased to 7 percent in 2017. It is expected to reach 23% in the year 2040 [1].Contrary to other renewable energy sources like wind power, the distribution of photo-voltaic power is easily integrated into the electrical network at any point.

PV power systems are mainly grouped in stand-alone and grid-connected systems. A PV grid-connected comprises the PV array, DC-DC converter(s), inverter(s), meters, grid connection as well as DC and AC cabling. The inverters are the most important elements for the integration.

Presently, the grid has settings that can be used to switch voltage and brand the grid steadier; the innovative inverters devices change DC solar power to AC power. In spite of replacing load parameters, as well as want to supply and also engross reactive power in the case of reactive loads, the inverters are vital to supplying continuous frequency and voltage. A PV installation's yield reliant on the reliability and the inverter's efficiency by the way of orientation, interconnection as well as the quality of PV modules. Notable challenges affecting the system of integration include voltage instability, frequency instability, and general power quality. In solar energy the two deviations are the main challenges in grid integration; voltage and frequency are not constant due to the quantity of irradiance.

The Static Volt-Ampere Reactive Compensator (SVC) needs reactors to absorb VARs from the system, dropping the voltage of the system if the reactive load of the power system is capacitive (leading). Below lagging (inductive) situations, the capacitor banks are automatically switched in, thus providing a higher system voltage [2]. To control system voltages, recover transient stability, upsurge transmission capacity, etc. the SVC's are suitable.

Contribution: For the first time, this paper presents the application of SVC with shunt control in the mitigation of PQ issues with increased solar integration to the power grid. A multi objective approach including the location and sizing of the SVC is employed. Simulation is done using Particle Swarm Optimization (PSO).

Paper Organization: The rest of the paper is organized as follows: Section II gives Literature Review, Section III is the Proposed Methodology, Section IV is Problem Formulation, Section V is the Presentation of Results and Analysis, while Section VI is the Conclusion and finally, there is a list of references used.

II. LITERATURE REVIEW

A. Power Supply Problems in PV System Integration

Many attentions required for the integration of solar energy to grid such as solar module manufacturing, connections, and operation among others. The solar energy needs to be unified efficiently on the transmission grid; such interconnection considering the belongings of the grid at numerous facts. Photovoltaic plant encompasses different elements but the very important element for integration is the inverter [1].The main function of an inverter is to invert the direct output to alternating current, which makes typically use by different devices. The inverters play essential role in supplying steady voltage and frequency, in spite of exchanging load conditions, and need to supply, alternatively reactive loads absorbing reactive power.

Integration of PV power to national distribution grids causes negative effects on its power quality, its reliability as well as the stability of the electricity network. Another impact is related to the bidirectional power flow from the protection of the equipment issues. From the design of the circuit, with the electrical installation position, have some impact on the voltage changes, network steadiness, voltage control, power quality and safety as well as harmonization. Contrary to conventional power plants, PV power plants lack rotor, therefore no inertia is present; the out power is highly solar radiation dependent. Any prompt fluctuation in solar radiation will cause changes in output power variations. For instance, during sunrise the PV output power increases rapidly and considerably. There is a possibility of reaching the maximum power in short period depending on the rise change of the inverters. Additionally, the change may result from the weather conditions in the vicinity of PV plants.

Finally, the absence of system voltage and frequency, power quality is deteriorated. Also compared to synchronous generators, the PV installations have no issues related to reconnection because they do not need synchronization. Once a fault is detected at network node that is connected to both network and PV generation, the breaker from the network opens to solve the faults. The challenges associated to PV integration vary from one power system to another based on the PV input intensity compared to the power system and their respective topography.

B. Static Var Compensator Description

The SVC controls voltage terminals by monitoring the quantity of injected reactive power into or consumed along the power system. When the system voltage is high, the SVC produces reactive power (SVC capacitive), on the contrast it absorbs reactive power (SVC inductive) [2]. Fast response, extensive operational range and high reliability are the most characteristics of a Static Var Compensator device. To produce and regulate reactive power, the thyristor valves are required practically in combination with capacitor and reactor banks from several methods. The key function of the SVC is to control the voltage at desired bus in monitoring the injected reactive power at that particular point. It is very suitable to maintain or to keep the levels of esteemed voltage for functioning and using loads. In a simple system, the SVC contains a thyristor-controlled reactor, mounted in parallel with a capacitors' bank [3].

The SVC's schematic design is shown as shunt-connected device in figure 1, comprising TCR and TSCs. The SVC is an automated device aimed at bringing the power factor of the system closer to unity [2]. Additionally, SVC experience parallel connection with line and central role is controlling the voltage at a particular bus by regulating its corresponding reactance. SVCs can be used in two main cases, i.e when is connected to the power system for regulating the transmission voltage ("Transmission SVC") and when is connected near large industrial loads for improving the power quality ("Industrial SVC").

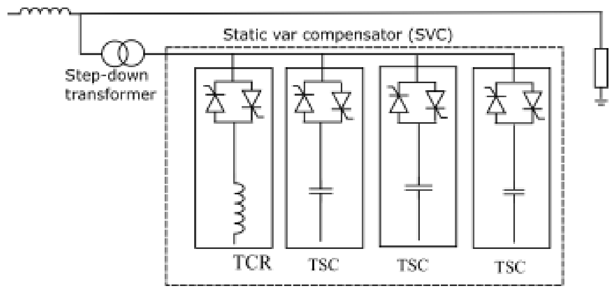

Fig. 1. SVC of the TCR-TSC Type [4].

III. METHODOLOGY

This section discusses the methods used to design the svc for improving the power supply of solar energy connected to the grid. In summary, it discusses the previous methods applied to the problem, the optimization and simulation tool and the mapping method to the problem.

A. Previous Methods

Uncertainty, there exist extreme reactive power injection by the system components or the customers' loads, the system's voltage increases while introducing excessive reactive power it goes low. However, the voltage's unreliability produced by the change in the required reactive power by the elements of the system and the customers' loads.

Several methods have been used to accomplish this such as system's structure reconfiguration, regulating generator excitation, synchronizing generator, variating the voltage by transformer's tap to regulate the power flow in the network, series compensation capacitor, switching in/out the shunt-reactor or shunt-capacitor are the traditional approaches used. Through these approaches the wanted objectives were not efficiently attained by attire and tear in the mechanical elements and slow response being the main glitches [5].

In 2019, [6] used SVC in a subsystem of 150KV to improve the voltage quality in West Java in Indonesia. As results, the implementation of SVC improved the voltage loss to 13.56 percent at Cibatu IBT 3-4 subsystem and the transmission line. In [7], authors discussed about Dragonfly algorithm and used this algorithm on IEEE 14 and 30 bus systems to study the size and cost of the SVC, voltage fluctuation and regulation of Static VAR during design process. A significant improvement of the voltage profile was noted using 100MVAR-SVCs.

However, it has been observed that voltage enhancement and power loss minimization are analyzed in unrealistic conditions (a one-time step) e.g. [8], [9].

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Briefly, use of FACTS devices in dealing with power quality including voltage stability is well documented and new technology and algorithm are still under discussion [6], [7], [8], [9], [10], [11]. The majority of all existing methods suggested by cited in this study, optimize the allocation and settings of SVCs for dynamic voltage recovery or angular stability improvement.

B. Mapping Method to the Problem

Eberhart and Kennedy (1995) established Particle Swarm Optimization (PSO) as an optimization approach. It is mainly enthused from the behavior of the flock of bird and schooling of fish. In this manner, the system is initially attuned with a set of random answers and the optimization search is guaranteed by informing peers [12]. It is showed that the PSO provided improved answer quality and a lesser quantity of iterations compared to Genetic Algorithm (GA) technique. In comparison with GA, the PSO grants a shorter computational time and can be altered to actual cases for power networks. Few advantages and disadvantages of the PSO are presented below:

The advantages: To implement is simple; Need few constraints to regulate; have advanced possibility and efficacy in discovery the universal targets; Have short computational time.

The disadvantages: Can be hard to describe preliminary design parameters;Not operate out the problems of handful, etc. In a PSO system, the particles move in a complex search space. Each particle regulates its individual position and based on the knowledge of the nearest particle, utilizes the finest location came across by itself and its nearest, during flight [13].

IV. PROBLEM FORMULATION

In this section, the multi-objective function is expressed to find optimal location and size of SVC device by decreasing certain objective functions subject to sufficient network constraints.

Mathematical model of SVC: It is a shunt-connected static var generator or absorber whose output is attuned to argument capacitive or inductive current thus to keep and regulate exact parameters of the electrical power system (typically bus voltage). It is demonstrated as an ideal reactive power injection at the load ends [14]. The SVC current is expressed as follows

$$I_{\text{SVC}} = jB_{\text{SVC}}V_{\text{k}} \tag{1}$$

The SVC reactive power, which is also the reactive power injected at bus k, is drawn:

$$Q_{\text{SVC}} = Q_{\text{k}} = -V_k^2 B_{\text{SVC}} \tag{2}$$

Where B_{SVC}= the susceptance of SVC and V_{k} = the voltage at bus k.

Mathematical model of PSO: The swarm of individuals(particles) reset with a group (population) of arbitrary candidate solution change through the problem of d-dimension space to hunt the novel answers. The suitable position, pbest, is calculated. Respectively, each individual has its own location and speed. The suitable (best) location amongst the swarms, gbest, is updated in every iteration [14]. Their respective location and speed are updated following equations:

$$V_{\text{k}}^{\text{n+1}} = W_{\text{k}}V_{\text{k}}^{\text{n}} + C_1 \times rand_1(pbest_{\text{k}} \times S_{\text{k}}^{\text{n}}) + C_2 \times rand_2 \times (gbest_{\text{k}} - S_{\text{k}}^{\text{n}}) \tag{3}$$

Where,

$$S_{\text{k}}^{\text{n+1}} = S_{\text{k}}^{\text{n}} + V_{\text{k}}^{\text{n+1}} \tag{4}$$

$$W = W_{max} - \left(\frac{W_{max} - W_{min}}{iterw_{max}}\right) \times iter \tag{5}$$

V_k^n= Velocity of k^{th} particle at n^{th} iteration; V_k^{n+1}= Velocity of k^{th} particle at $(n+1)^{th}$ iteration; S_k^n= Current location of particle k at nth iteration; S_k^{n+1}= Current location of particle k at $(n+1)^{th}$ iteration; $pbest_k$= individual suitable position of k^{th} particle; $gbest_k$ = Best global position of swarm (entire group of the particles); C_1= Coefficient of the self-recognition component; C_2 = Coefficient of the social component; $C_1 + C_2 = 4$ $rand_1$ and $rand_2$ are the random numbers usually chosen between [0, 1]; W= Inertia weight; W_{max}= Maximum value of inertia weight; W_{min}= Minimum value of inertia weight; $iter$ = Present iteration; $iterw_{max}$ = Maximum iteration.
The objective function is given:

$$minf = P_{\text{Loss}} + \lambda VD \tag{6}$$

Where λ is the penalty co-efficient to give equal weightage for losses and VD is the voltage deviation.
The deviation of voltage at individually loaded bus have to be reduced as much as possible.

$$VD = \sum_{n=1}^{N_{PQ}} |V_m - V_{ref}| \tag{7}$$

So,

$$P_{\text{Loss}} = \sum_{n=1}^{N_L} G_{\text{mn}}(V_m^2 + V_n^2 - 2V_mV_n cos\delta_{mn}) \tag{8}$$

Where V_m= The voltage magnitude at bus m; V_n= The voltage magnitude at bus n; V_{ref}= The reference voltage; G_{mn}= The conductance of line m-n; δ_m= The voltage angle at bus i; N_L= The total number of transmission lines.

V. RESULTS AND DISCUSSION

This section demonstrates the improvement of power supply connected to the grid using static var compensator will focus on voltage and power quality. A fourteen-bus system is used to evaluate the efficiency of SVC. The efficiency of the proposed approach has been illustrated using the IEEE 14 bus test system shown in Figure 2. This network comprises six generators of which one is slack and there are 20 lines. The proposed practice has been verified on IEEE14-bus system,

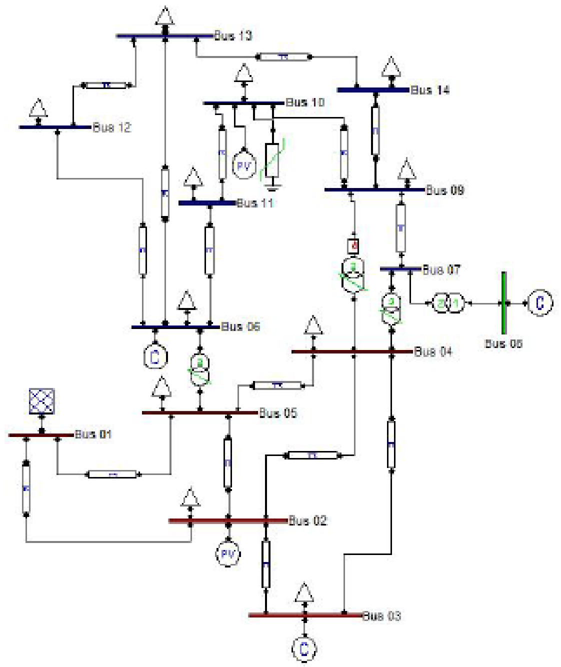

Fig. 2. IEEE 14 Bus system with SVC.

bus 2 and 10 are PV buses then 3, 6 and 8 are synchronous compensator buses and the load is modeled by PQ model.

The figure 3 illustrates the SVC result on voltage stability. It can be observed that the installation of the SVC increases the voltage stability compared to the base situation deprived of SVC. The figure proves that best location of SVC slightly attuned the voltages of PV buses and reducing the losses. The figure obviously shows that the buses voltages are in set of bounds at smallest active power loss with SVC at optimum position. A remarkable voltage improvement is only observed at bus no. 14 (Fig. 3, increase of 0.3 p.u) and power generation decreased by 10% p.u.

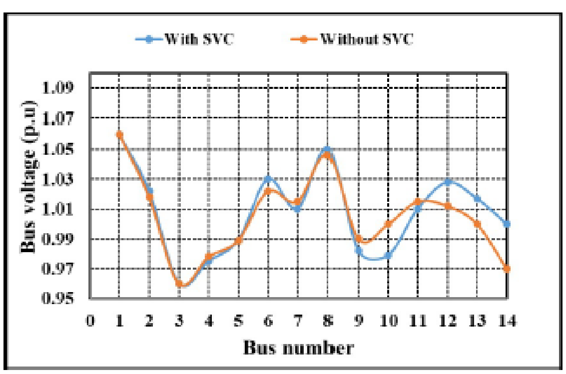

Fig. 3. Voltage profiles with and without SVC.

The active power flows in numerous positions are shown in Figure 4. The reduction in line losses is illustrated and the black line corresponds to the power flows with SVC and the red line represents the power flows without SVC. The losses are decreased once the SVC is optimally positioned.

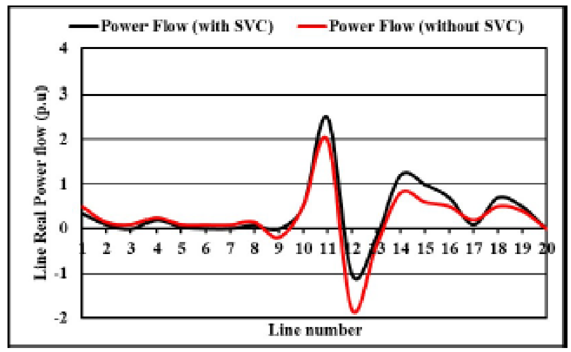

Fig. 4. Power flows with SVC and without SVC.

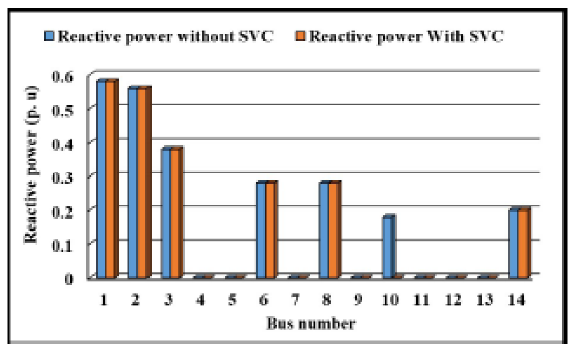

Fig. 5. Reactive Power Generation with and without SVC.

Figure 5 displays the bus generations at minimum reactive power loss with SVC at optimum place. The thick dark black bar signifies the generation at minimum reactive power loss by means of SVC and the white bars, the base state deprived of SVC.

CONCLUSION

In this work, SVC is used to improve the power system voltage stability. The absence of reactive power stretches positively to voltage instability, particularly once generators reach their bounds of reactive power production. Therefore, suitable compensation recovers and regulates voltage stability. The optimal introduction of SVC with particle swarm optimization technique presented a noticeable enhancement in the voltage stability with a comparatively small number of iterations and particles, therefore with a practical computational effort. The connection of the SVC in IEEE 14-bus providing well-enhanced voltage stability, the particle swarm optimization-based algorithm has been used to get the smallest voltage deviation and active power loss by optimally tracing of SVC device.

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A3: Similarity Report

Application of Static Var Compensator (SVC) for Improving Power Quality of Grid Connected Solar Energy

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