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PERFORMANCE ENHANCEMENT OF A RADIAL DISTRIBUTION SYSTEM WITH INTEGRATION OF SOLAR PHOTOVOLTAIC GENERATION SYSTEM

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Abstract: This paper assesses the performance of 11kV radial distribution system with its associated 0.415kV distributors of Ken Saro Wiwa Polytechnic Campus, Bori in Nigeria, with the aim of enhancing its performance through injection of Solar PV generation system. Load flow study simulation of the existing 11kV distribution network was carried out using Newton Raphson method embedded in Electrical Transient Analyzer Program software, so as to ascertain the network state and check if it meets up expectation. In order to enhance the distribution network, analytical technique was used to size a Solar PV generation system which was incorporated into the network and load flow study was repeated. The results obtained indicate nine (9) out of the thirteen (13) buses of the existing case network were marginally and critically overloaded. The net real and reactive power losses was 22.634kW and 16.897kVar respectively. But at the instance of injecting a sizable Solar PV generation system (425.8kW), the outcome shows that all the buses in the network are all in normal operating conditions. The net real power losses reduced from 22.634kW to 7.296KW and the reactive power losses reduced from 16.897kVar to 4.279KVar, which implies that there is 67.8% reduction in real power loss and 75% reduction in reactive power loss when solar PV generation system is penetrated, and the voltage profile of all the buses fall within ±5% variation as declared by IEEE. All these indicates that the system performance has been significantly improved,

Keywords: Newton Raphson, Electrical Transient Analyzer Program, Real Power, Reactive Power, Voltage Profile, IEEE

I. INTRODUCTION

In modern age, electricity is an essential requirement for all human endeavours. It is now been accepted as a basic human need, and also been asserted that rapid socio-economic development, technological advancement and industrialization of any country depends on it [1]. The electric power system consists of three primary sections namely; generation section, transmission section, and distribution section. The distribution system is the most visible part of the power supply chain, since it is a service of electrical circuits that delivers power in specified proportion to domestic, commercial and industrial consumers [2]. Therefore, the most exposed to the critical observation of its users. The utility company goal is to achieve certain sufficient levels of reliability, stability and quality power supply to serve the maximum load [3]. In developing countries such as; Nigeria, there is a large mismatch between units of energy generated by the on-grid power generating stations and units of energy demanded by the consumers. Inadequate power generation has been known as the enormous factor responsible for the energy mismatch. Other contributing factors includes: poor transmission feeder, inefficient voltage control mechanism, and faulty distribution system which results to excessive voltage drop and huge power losses along the distribution feeders [4]. The subject of distribution system losses and unacceptable voltage deviation has gained a great deal of attention in power system operation due to rising fossil fuel prices as a result of dwindling reserves, which has led to high cost of electrical energy [5][6]

Nigeria is endowed with rich renewable energy resources that can be used in generating electricity, the substantial ones being solar, biomass and wind. Power system planners have to come up with approaches to ameliorate the lack of access or inadequate electricity supply to the consumers using a mixture of fossil fuel and the available renewable energy resources for power generation in order to reduce losses during transmission, while preserving the environment [7][8]. This reason motivates this research, to enhance the performance of a typical radial distribution system with injection of solar photovoltaic energy generating system.

II. Statement of the Problem

Inadequate and unstable power supply has been a burning issue hampering the smooth operation of power system in Nigeria. The 11kV distribution network supplying power to the two campuses of Ken Saro Wiwa polytechnic, Bori in Rivers state has been experiencing incessant power outage, low voltage profile, excessive power losses, and sometimes rapid blackout. This has resulted to decline in quality education delivery and loss of revenue by the utility supplying power to the school. In summary, the insufficient power supply in the area slows down the socio-economic development and technological advancement of the nation.

In order to mitigate the problem, the school management has been supplying power for a maximum of four hours a day using diesel generator, which is neither enough nor economical and sustainable. This research will propose performance enhancement of the distribution system with injection of solar photovoltaic generation system for quality power supply.

III. LITERATURE REVIEW

The introduction of distributed generation (DG) such as solar photovoltaic system in the distribution network will effectively improve the active electric power loss reduction, this approach is one of ways by which power losses can be minimized in a distribution feeder by optimizing distributed generation (DG) model using suitable techniques in determining the size, location and operating point of the DG [9]. Several distributed generation technologies are under various stages of development. They include micro turbines photovoltaic system (PV) wind energy conversion system (WECS), gas turbine, diesel engines and fuel cell system. But presently, wind energy and photovoltaic system has become among or most competitive among all renewable energy technologies [10].

According to [11], they presented a paper on using hybrid algorithm (PSO & HBMO) for optimal integration and sizing of electrical distributed generation (DG) in a radial distribution system so as improve the voltage profile and reduces the total power losses of a 13-bus radial distribution system. MATLAB software was used as the simulation tool. The result obtained shows that the technique has the capacity to be a tool to identify the best location and rating of a DG to be integrated for enhancing the voltage profile and power losses reduction in an electrical power system.

In the paper presented by [12], they analyzed potential and practicality of a grid connected PV system in Bangladesh using a proposed 1MW grid connected solar PV system in fourteen diverse places in the country. The author’s utilize Geospatial toolbox, NASA SSE solar radiation information. Homer and RET screen simulation programs were used. The investigation presumed that all the pointers’ favours sending of the proposed PV system and that unit cost of the system is lower than grid connected fuel oil-based power generation.

In the study proposed by [13], comparative analysis of off-grid hybrid of small Hydro-Solar Photovoltaic-Diesel generator system was carried out in three selected locations in South-west, Nigeria. The data used for the analysis was collected from River Basin Development Authorities and National Aeronautics and Space Administration’s global satellite website. Hybrid Optimization Model for Electric Renewable (HOMER) software was used for simulation.

The results obtained shows that hybrid power generating system with renewable resources are viable, based on economic and technical considerations.

- **Solar Power Plant**

Solar power plants are plants that convert sunlight into electrical energy. This is achieved in two ways, using photovoltaic (PV) or concentrated solar power (CSP). A PV system basically uses photovoltaic effect to convert energy from the sun into electrical energy [14]. The applications of PV in generating electricity have grown from off-grid rooftop PV system into commercial application where thousands of grid connected/linked PV power plants are generating megawatts of electricity. Solar PV plants are of two types, off-grid and grid connected. Off-grid refers to a system where PV system only supplies electricity to the building and has no connection to public utility supply. Grid connected refers to a system where the surplus power generated after electricity need of the organization is met is then sent to the public distribution grid. The grid connected can be designed to have battery back-up or without battery back-up [15].

IV. METHODOLOGY

The existing study case distribution network was modelled and simulated using embedded Newton Raphson technique in Electrical Transient Analyzer Program environment, for load flow studies. The system losses and voltage profiles at each bus in the network were recorded. Then, the system was upgraded by the penetration of sizable solar PV power generation system using analytical technique for its sizing. Load flow study was performed again with Solar PV System inclusion in the network. Tables 1, shows the load data of the network.

Table 1: Network Load Data at 80%PF

Transformer Location Name	Transformer Size (KVA)	Bus ID and Area Connected at 415KV	Load Connected (KVA)	Load Connected (KW)
T_2	500	Bus 6 (Lecture Hall)	80	64
		Bus 7 (Engr. Block)	80	64
		Bus (Mgt. Block)	80	64
		Bus 9 (Science Lab Block)		
		Bus 10 (Workshop Block)	30	24
		Bus 11 (Surveying Block)	60	48
T_3	500	Bus 12 (Eviron. Studio)	80	64
		Bus 13 (Off Camp Load)	80	64
		Bus 14 (Drawing Studio)	80	64
			50	40

Source: Port Harcourt Electricity Distribution Company (PHEDC)

- **Newton Raphson Load Flow Technique**

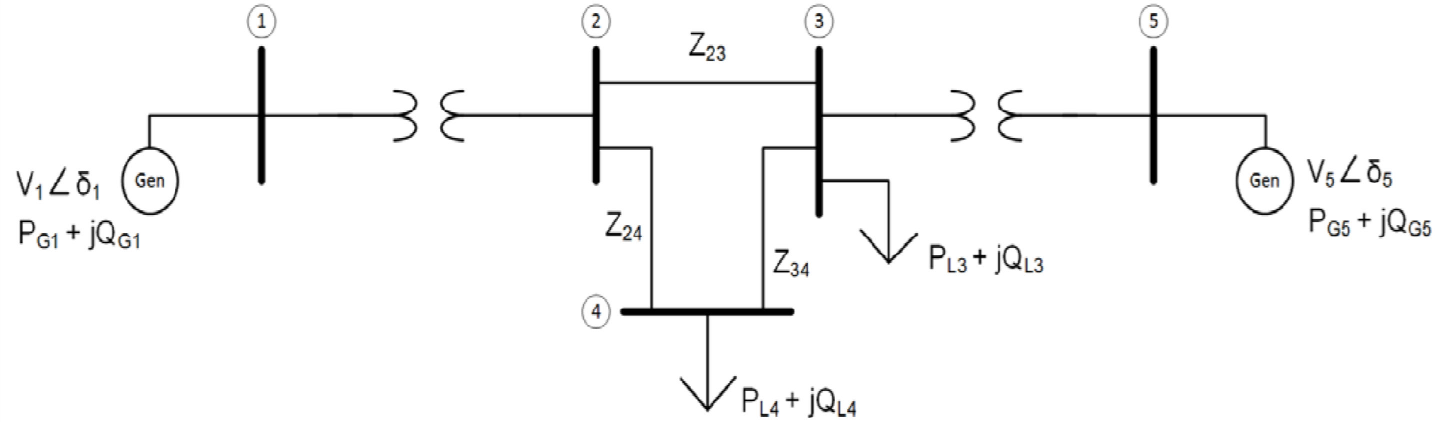

Figure 1: Single Line Diagram of a Power System.

The apparent power injected at the *ith* node is

$S_i = V_i I_i^* = P_i + jQ_i$ (1.1)

$I_i = \left(\frac{S_i}{V_i}\right)^* = \frac{P_i - jQ_i}{V_i^*}$ (1.2)

$I_i = \frac{P_i - jQ_i}{V_i^*} = \sum_{k=1}^{n} Y_{ik} V_k$ (1.3)

$P_i - jQ_i = V_i^* (\sum_{k=1}^{n} Y_{ik} V_k)$ (1.4)

Let $V_i^* = V_{\text{i}}\angle - \delta_i, V_k = V_{\text{k}}\angle\delta_k$ and $Y_{ik} = Y_{\text{ik}}\angle\theta_{ik}$

$P_i - jQ_i = V_i \ (\sum_{k=1}^{n} Y_{ik} V_k \angle\delta_k + \theta_{ik} - \delta_i)$ (1.5)

$P_i - jQ_i = \sum_{k=1}^{n} |Y_{ik}||V_{\text{i}}||V_{\text{k}}| \, [\cos(\delta_k + \theta_{ik} - \delta_i) + j \sin(\delta_k + \theta_{ik} - \delta_i)]$ (1.6)

Separating the real part from the imaginary part in (1.6)

$P_i = \sum_{k=1}^{n} |Y_{ik}||V_{\text{i}}||V_{\text{k}}| \cos(\delta_k + \theta_{ik} - \delta_i)$ (1.7)

$Q_i = -\sum_{k=1}^{n} |Y_{ik}||V_{\text{i}}||V_{\text{k}}| \sin(\delta_k + \theta_{ik} - \delta_i)$ (1.8)

Where

Y_{ik}= admittance

P_i= real power

Q_i= reactive power

δ_i= phase angle

Expanding (1.7) and (1.8) in Taylors series neglecting higher order terms we have

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \begin{bmatrix} \begin{vmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} \end{vmatrix} & \begin{vmatrix} \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \end{vmatrix} \\ \begin{vmatrix} \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} \end{vmatrix} & \begin{vmatrix} \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{vmatrix} \end{bmatrix} \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \\ \Delta \left|V_2^{(k)}\right| \\ \vdots \\ \Delta \left|V_n^{(k)}\right| \end{bmatrix} \quad (1.9)$$

With minor changes in real $\Delta P_i^{(k)}$ and reactive power $\Delta Q_i^{(k)}$the Jacobian matrix shows the linearized correlation between tiny changes in voltage angle $\Delta \delta_i^{(k)}$ and magnitude $\Delta \left|V_i^{(k)}\right|$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_3 \\ J_2 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \quad (1.10)$$

Where

J_1, J_2, J_3, J_4 are the elements of the Jacobian matrix

The diagonal and the off-diagonal elements of J_1 are

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{k \neq i} |Y_{ik}||V_\mathrm{i}||V_\mathrm{k}| \sin(\delta_k + \theta_{ik} - \delta_i) \quad (1.11)$$

$$\frac{\partial P_i}{\partial \delta_k} = -|Y_{ik}||V_\mathrm{i}||V_\mathrm{k}| \sin(\delta_k + \theta_{ik} - \delta_i) \qquad k \neq i \quad (1.12)$$

Similarly, the diagonal and off diagonal element of J_2, J_3, J_4 can be computed

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)} \quad (1.13)$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \quad (1.14)$$

Equations 1.1 to 1.14 are the fundamental power flow equations and its solution is facilitated using the traditional Newton Raphson solution algorithm embedded in ETAP

Sizing Photovoltaic Power Generation System

According to [16], Photovoltaic power generation system size can be evaluated as shown (1.15)

DG size = Full Load + Reserve Capacity (1.15)

Where:

Full Load (kW) = $\frac{Total\ amps\ x\ supply\ Voltage\ (V)}{1000}$

Reserve Capacity = 25% of full load (kW)

Total current drawn from Campus 1 and 2

= 3861 + 434.8 = 820.9A

Full load (kW)= $\frac{820.9\ X\ 415}{1000}$

= 340.67kW

Reserve Capacity = 0.25 x 340.67

= 85.2kW

DG Size = 340.67 + 85.2kW

= 425.84KW or 426kW

V. RESULTS AND DISCUSSIONS

- **Simulation Diagrams with and Without Solar PV Generation System.**

Figures 2 and Figure 3 depict the one-line simulation diagrams of the study case network without and with Solar PV generation system injection respectively. As shown in Figure 2, the base case, five (5) load buses are critically loaded (Red colour) while the remaining four (4) load buses indicate marginally loading conditions (Purple colour). As shown in Figure 3, with the penetration of 425.8kW of Solar PV generation system, all the defective load buses were upgraded from critical and marginal loading conditions to normal operating conditions (Black colour).

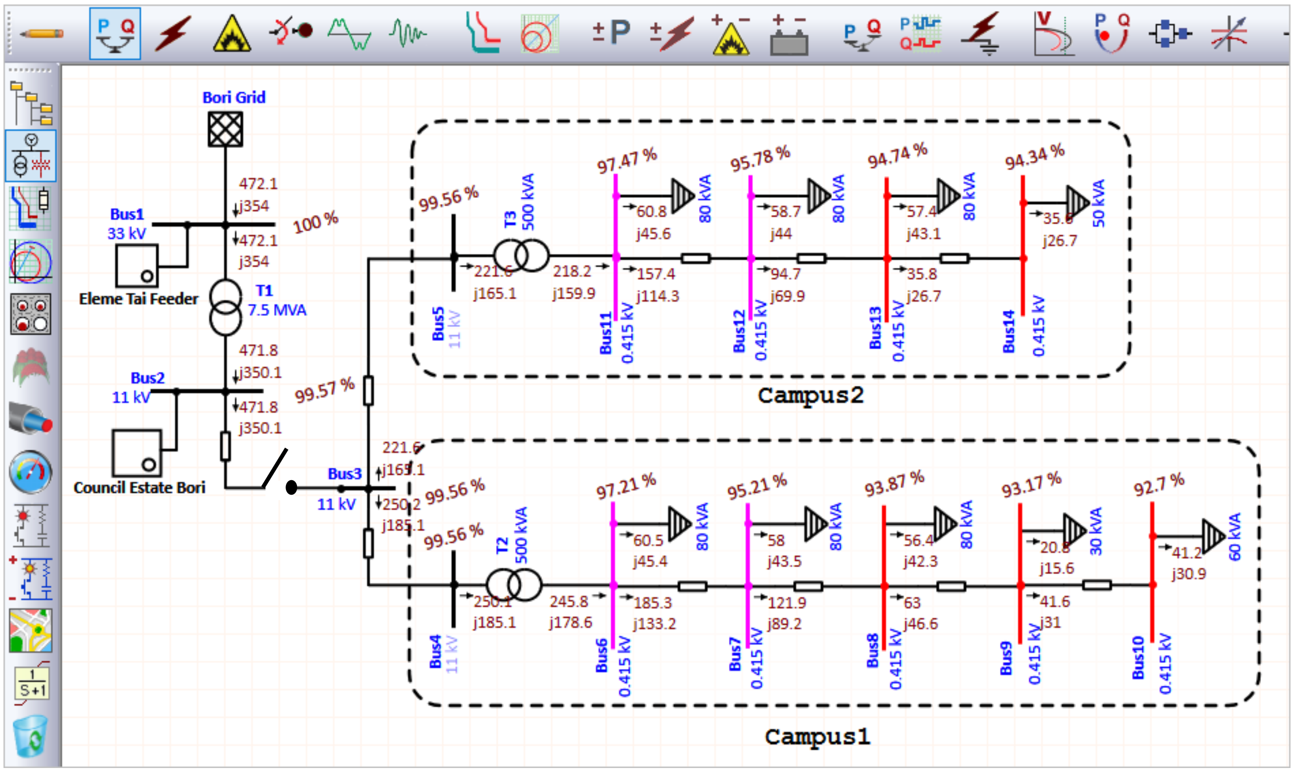

Figure 2: Simulated Network without Solar PV Penetration.

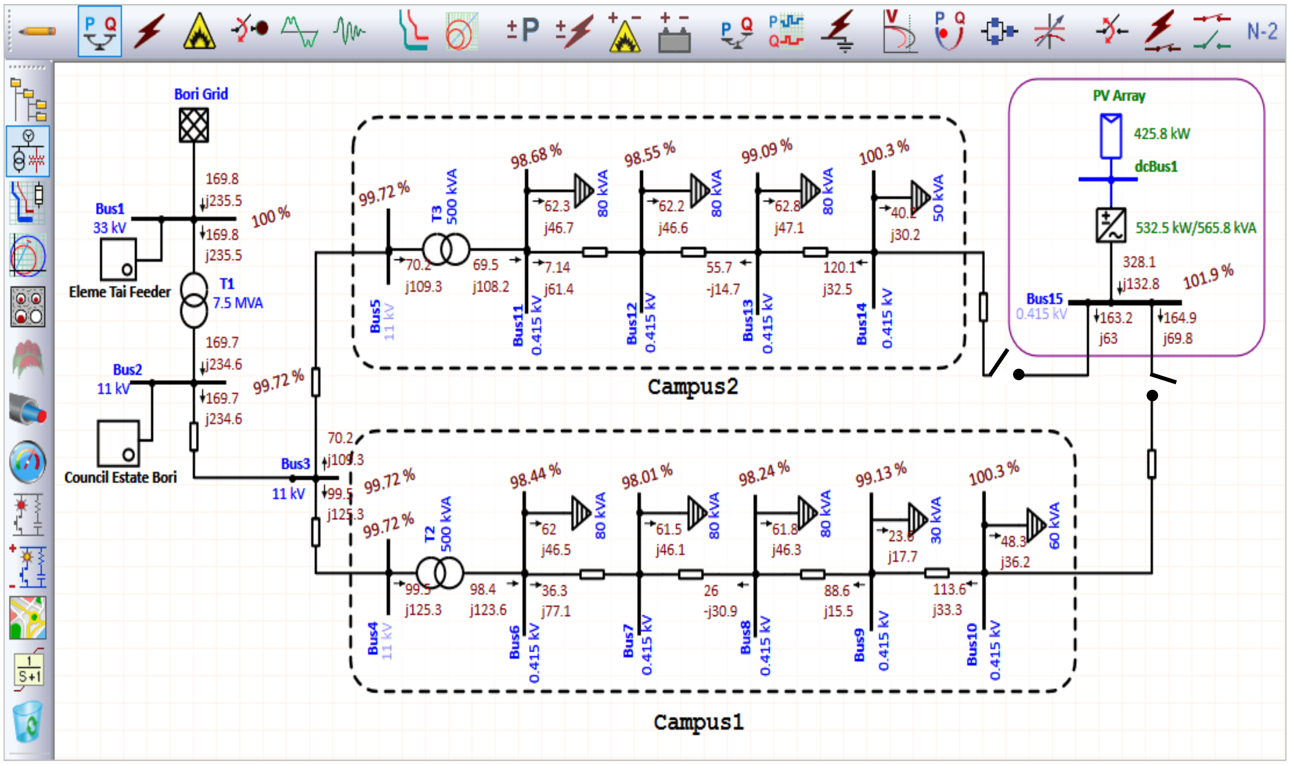

Figure 3: Simulated Network with Solar PV Penetration

- **Bus Voltage Profile with and Without Solar PV Generation System**

Figure 4 shows a composite bar chart illustrating the percentage of bus voltage magnitude with and without penetration of Solar PV generation system in the network. Without injection of Solar PV system in the network, it was observed that nine (9) buses (6,7,8,9,10,11,12,13,14) out of the thirteen (13) buses indicate violation of statutory voltage deviation limit of +5% of nominal voltage as declared by IEEE. After the injection of Solar PV generation system (425.8kW), all the buses are now under normal operating conditions and there is no violations of voltage statutory limit as stipulated IEEE

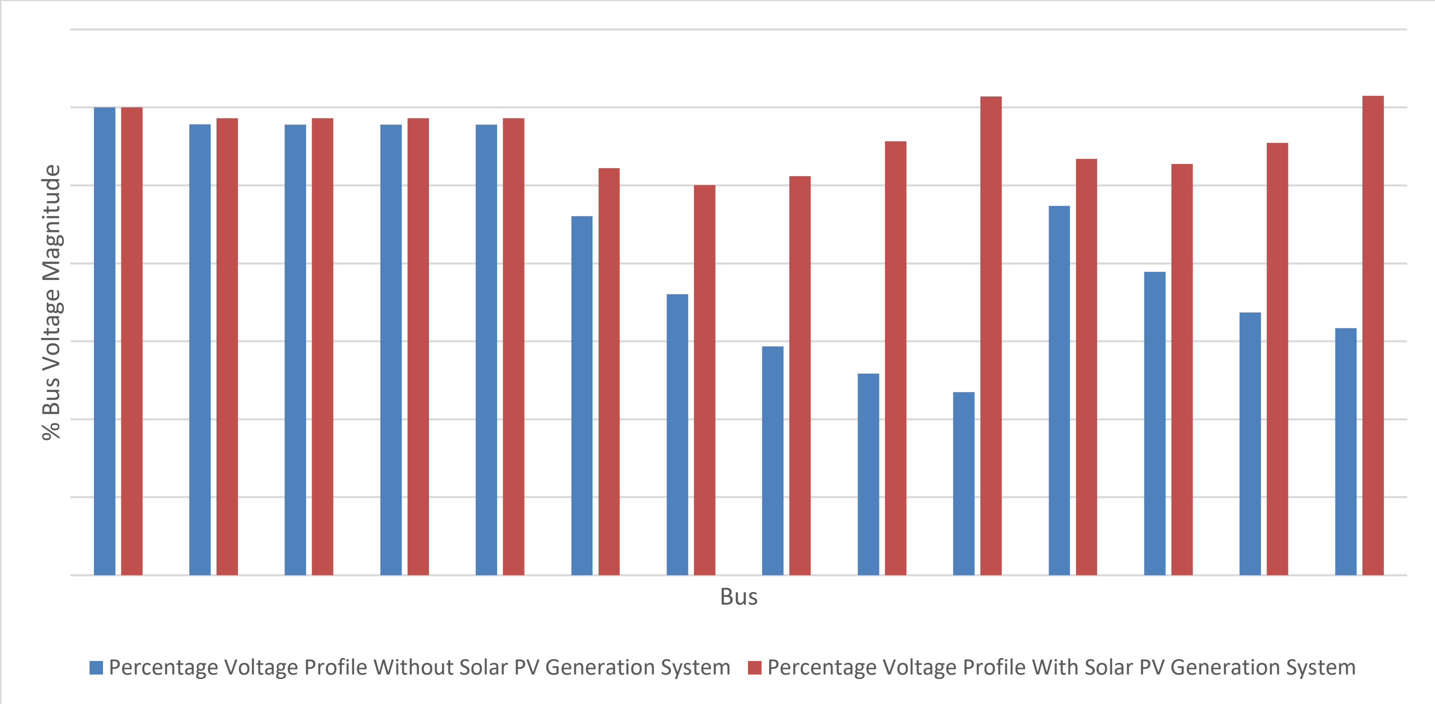

Figure 4: Composite Bar Chart of Percentage Bus Voltage Magnitude

- **Real Power Loss with and Without Solar PV Generation System**

Figure 5 depicts line graphs illustrating the real power losses in the network with and without Solar PV generation. With the injection of Solar PV system (425.8kW) in the network, there is a significant reduction in real power loss. The total real power loss without Solar PV system was 22.634kW, while with Solar PV system is 7.296kW.

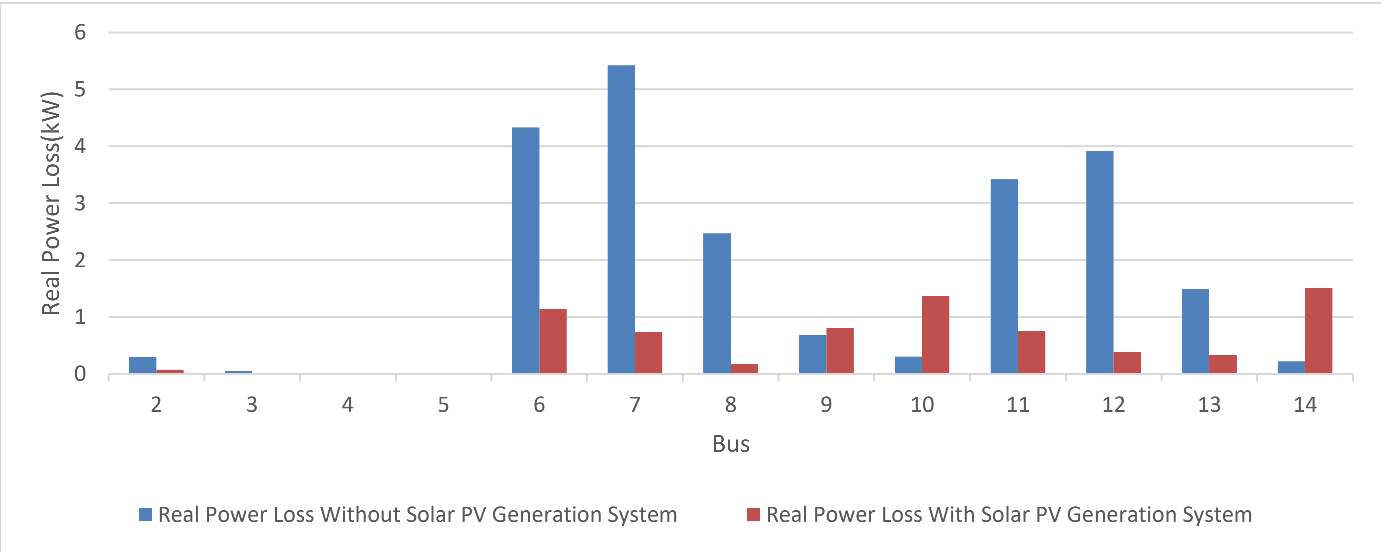

Figure 5: Line Graph of Real Power Loss

- **Reactive Power Loss with and without Solar PV Generation System**

Figure 6 shows line graphs illustrating the reactive power losses in the network with and without Solar PV generation. With the penetration of Solar PV system (425.8kW) in the network, there is an appreciable reduction in reactive power loss. The total real power loss with and without Solar PV system is 4.279kVar and 16.879kVar respectively.

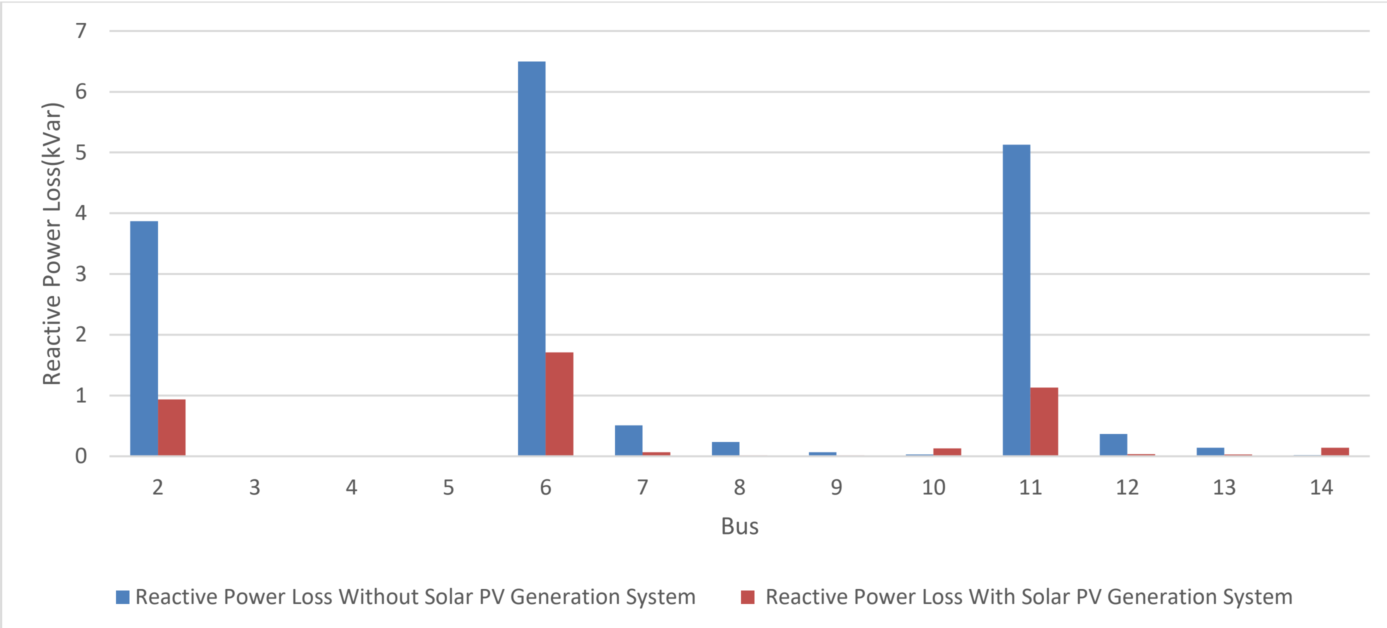

Figure 6: Line Graph of Reactive Power Loss.

5. Conclusion

This performance of a radial distribution system can be enhanced with the penetration of Solar PV generation system to achieve stable operating condition of the power system. This study carried out performance enhancement of 11kV distribution system with its associated 0.415kV distributors via penetration of Solar PV generation system. Load flow study of the network was performed using Electrical Transient Analyzer Program (ETAP) simulation tool to ascertain the existing condition of the network. In order to enhance the performance of the system, Solar PV generation system was penetrated into the network using analytical technique for its sizing. The results obtained shows that when a sizable Solar PV generation system (425.8kW) was injected into the network, the total real power loss reduced from 22.634kW to 7.296KW, and the total reactive power loss reduced from 16.879kVar to 4.279kVar. This means that at the instance of injecting Solar PV System (425.8KW) into the network, the real and reactive power losses reduced by 67.8% and 75% respectively, and all the bus voltage falls within IEEE voltage variation benchmark.

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