Battery Energy Storage based Approach for Grid Voltage Regulation in Renewable Rich Distribution Networks

Vimukthi Gamage
Department of Electrical Engineering
University of Moratuwa
Moratuwa, Sri Lanka
gamage.vimukthi197@gmail.com

Nishan Withana
Department of Electrical Engineering
University of Moratuwa
Moratuwa, Sri Lanka
nishanrandika@gmail.com

Channa Silva
Department of Electrical Engineering
University of Moratuwa
Moratuwa, Sri Lanka
glchannasilva@gmail.com

Rasara Samarasinghe
Department of Electrical Engineering
University of Moratuwa
Moratuwa, Sri Lanka
rasaras@uom.lk

***Abstract*— In consequence to the proliferation of Distributed Energy Resources alongside nonlinear power electronic devices in electrical power distribution systems during recent past, the fluctuations in the grid voltage as well as in the current has elevated to a significant level provoking a higher concern over the capability of utility voltage regulators in delivering power with a higher reliability and higher quality. Vast amount of research is being carried out to unravel this condition and elucidate a potential solution while the current power system is sustaining with the upgrades of certain technological improvements. This paper proposes a method which utilizes a Battery Energy Storage System to be incorporated with a grid connected solar photovoltaic system to facilitate the voltage regulation in the utility side. The battery energy storage system is expected to store energy during high solar photovoltaic generation or low power demanding conditions while supplying energy back to the system during low solar photovoltaic generation or high-power demanding conditions. The modeling and simulation of the proposed system is implemented, and the system performance is investigated for several circumstances with varied solar photovoltaic generation for different battery states.**

Keywords*— Battery energy storage systems, solar photovoltaic systems, energy storage systems, grid voltage regulation, renewable energy

I. INTRODUCTION

Energy is a basic element which governs the balance of the world. Sun being the primary source of the energy plays a prominent role in governing the aforementioned balance. Since the invention of the fire, people have been involved in altering the natural cycles of environment. Implications of the human involvement is lucid as the world is faced with a big conundrum to deal with.

Invention of electricity along with the power generation methods aggravated the impact of the adverse effects of human doings. Initially people were using the biomass, carbon neutral fuel, as the main source of energy. With the increasing population, demand for energy climbed sharply. Therefore use of energy sources such as coal, and oil grew over time while emitting tons of greenhouse gases (Carbon Dioxide, SOx, NOx) into the atmosphere. Now we have reached a situation where reduction of the greenhouse gas emissions is imminent if we are to limit the global temperature rise to an acceptable level. Hence, inevitably the focus has shifted to renewable energy generation methods, which have low environmental impact compared to the traditional power generating methods.

Biomass, wind, small hydro, geothermal, solar photovoltaic, solar thermal and tidal power are main renewable power generation methods used in the present context. Renewable generation went through a rapid growth in capacity especially with the developments in the solar photovoltaic technology. Solar photovoltaic capacity generation consists both distributed generation and large scale solar farms. Some countries focused more on distributed generation resulting in large uncontrollable power generation, which consequently gave rise to a unique set of problems associated with distributed power generation. Voltage variations, two way power flow, degraded protection, and increased fault level are some of those commonly encountered issues caused due to high penetration of renewable generation [1].

Considerable amount of research work is carried out in the field of grid voltage regulation in distribution networks and islanded systems such as micro-grids. Methods of reactive power management in renewable rich power grids have been looked into in [2]–[4] considering wind, solar pv (photovoltaics) and reactive power support devices.

[5] provides an approach of coordinated and integrated control of solar pv generators with MPPT control and battery storage control to provide voltage and frequency support to an islanded micro-grid.

There are various challenges faced when integrating solar power to the distribution networks which can be reduced by integrating Battery Energy Storage systems (BESS) in grid tie applications [6]. Coordinated use of solar PV and Battery Storage Systems in a certain feeder to address voltage issues (dip/rise) is presented in [7].

Apart from evaluating the technical feasibility of using energy storage systems to mitigate voltage issues, financial and economic feasibility should also be considered. [8] presents an economic feasibility of battery storage for residential solar PV system in Germany. Quadratic programming based algorithm prioritizing peak demand management, suppression of voltage swings, and maximization of daily financial savings is presented in [9].

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Frequency deviations of the distribution network are usually handled by the system control centre which balances the demand and the generation using the all the dispatchable power plants is the network. However, battery storage systems in large scale solar photovoltaic plants can also be used to assist the frequency control.

In this paper, effect of introducing a battery based system at each node (consumer unit) in a radial distribution line is investigated mainly considering the Sri Lankan power grid. However, this is a general application which can be implemented in any other power grid as well. The outline of the paper is as follows. Section II discusses the energy storage systems, followed by the details of the battery energy storage technologies, theoretical and mathematical background of voltage regulation, and modeling and simulation of the proposed system in section III, IV and V. Simulation results are explained in Section VI, and section VII concludes the paper.

II. Energy Storage Systems

Energy storage systems are used with the main intention of storing energy to later convert that energy to the electrical energy [10]. Generally electricity is generated as it is consumed. However, with the addition of the new renewable energy into the generation mix, electricity is generated when it is not actually required for consumption. Hence, significance of energy storage has recently been increased. Energy storage provides solutions to issues such as random fluctuations of the renewable generation, power quality and reliability issues, voltage fluctuations, necessity for backup power and increased losses of the system.

Possible energy storage systems consist of; Pumped Storage Hydropower, Compressed Air Energy Storage (CAES), Battery Energy Storage, Fuel Cells, Thermal Energy Storage, Flywheels, Super Capacitors, Superconducting Magnetic Energy Storage (SMES), and Liquid Air Energy Storage [10], [11].

Out of the above options, pumped storage has been the most popular Energy Storage System. Currently there are about 180000 MW capacity of installed in the world. Electrochemical (battery), Thermal Storage, and Electromechanical storage have around 2500 – 3500 MW of capacity each [10]. However, the energy conversion efficiency is around 75% – 90% in these three technologies. Technologies such as capacitors, superconducting magnetic energy storage and flow batteries have higher efficiencies around 90%.

Another main consideration associated with Energy Storage Systems is that how quickly they can be taken on line. Some systems can deliver power rapidly. Capacitors take only 5ms to deliver power. Fly wheels and batteries can respond within tens of milliseconds. CAES systems take up to 2-3 mintues to deliver full power. Response time of pumped storage can take up to around 15 minutes [11].

Suitability of energy storage systems for small-scale renewable systems such as solar photovoltaic systems depends on factors including; size (energy density), cost, maturity of the technology and ease of implementation. Technologies such as CAES and pumped hydro are too large and costly to integrate with small-scale renewable systems. Infancy technologies including Super capacitors and SMES would still incorporate high project risk. Flow batteries, fuel cells, flywheels and battery energy storage systems are within the suitable cost and size of the system. However, battery technology is mature and possess higher energy density and also ease to install.

III. Battery Energy Storage Technologies

A. Battery Technologies

Widely used battery technologies are include; [11], [12].

1) Lead Acid batteries

Lead – acid battery technology is the most matured battery technology in the industry which is also widely used in distributed generation applications. Deep discharge type lead-acid batteries are more suited for small-scale renewable integration. They are capable of discharging up to 80% of the battery capacity. Hence, when properly managed, deep discharge type lead-acid batteries would be able to provide a solution to the voltage rise of the distribution feeder. Apart from that other benefits such as low self-discharge, lower initial investment, and ease of maintenance make the lead-acid batteries a competitive option for integrating with solar photovoltaic systems. However, drawbacks such as limited cycle life, performance deterioration at high and low temperatures, failures due to continuous and deep cycling, and large eco footprint due to acid electrolyte and lead content are inherent to lead-acid battery technology [12].

2) Nickel Cadmium batteries (NiCd)

Nickel Cadmium batteries possess higher energy density, longer cycle life and lower maintenance requirement compared to the Lead acid batteries making them a proven, robust and matured alternative to Lead acid batteries. Features such as cycling ability, long lifetime, durability and reliability of Nickel Cadmium batteries enable them to be integrated with solar photovoltaic systems. However drawbacks such as heavy metal content and severe self-discharge, discourage the use of Nickel cadmium batteries.

3) Nickel Metal Hydride batteries(NiMH)

NiMH batteries provides an alternative to NiCd batteries with better performance and less environmental impact. Though specific energy of NiMH batteries are superior to Lead acid and NiCd batteries, it is largely inferior to the Lithium ion batteries. Severe self-discharge is a concern in NiMH batteries too. However due to the better performance and lesser drawbacks compared with the Lead acid and NiCd counter parts, NiMH batteries provide a better possible solution to renewable integration applications.

4) Lithium ion batteries

Portable electronic equipment uses Lithium ion batteries as their power source. Lithium ion battery applications in automotive industry and renewable integration have also been increasing over the last decade. They have a higher energy density along with an energy storage efficiency of almost 100%. Higher initial cost and complicated charge management systems are the two main drawbacks. However research have been carried out improve these two aspects. Main constraint of integrating Lithium ion batteries with high percentages of renewable energy is the low average discharge duration of them. Average discharge duration of a Lithium ion battery is around 4 hours; even though it may vary from 0.5 hours to 8 hours, most of the operational Lithium ion batteries have a discharge duration less than 4 hours [12].

B. Battery Energy Storage System(BESS) with Renewable Energy

BESS can be connected to distribution networks at consumer level or as a centralized unit shared by a certain segment of the distribution network.

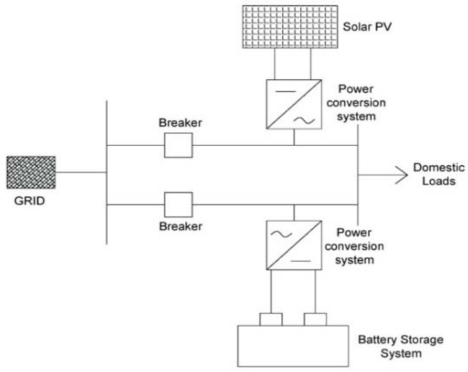

Fig. 1. Renewable generator and battery storage connected in parallel

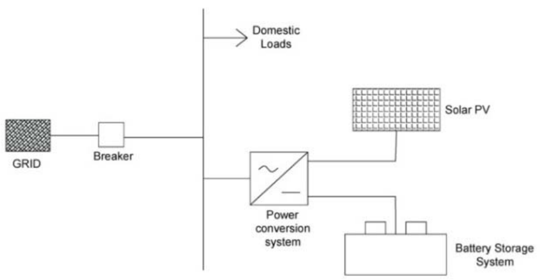

Fig. 2. Renewable generator and batteries connected through a hybrid inverter

1) At consumer level

Battery system can be connected to distribution network through a Hybrid grid tie inverter or by using a separate inverter. Integrating the BESS at the consumer end facilitates separate metering and more flexible dispatching compared to bulk connection.

2) Centralized unit

Ease of access, simple communication structure, economies of scale and ease of maintenance are the main advantages associated with a centralized unit [6]. However, separate metering is not available hence capital cost has to be incurred by the utility.

IV. Theoretical Background on Voltage Regulation

A. Mathematical Background

Voltage stability is a key component in maintaining power system stability. Maintaining the voltage with in the tolerance level is a must to achieve power quality. However, with high penetration of renewable energy, mainly that of the rooftop solar photovoltaic generation, has started to threaten the aforementioned voltage limit. The phenomenon is severe when large renewable generation occurs at times when the feeders are lightly loaded [6]. For an example, feeders with more domestic customers are lightly loaded at noon when the rooftop solar photovoltaics generate power at full capacity. As a result, feeder voltage increases. It may even lead to reverse power flow from low voltage distribution to medium voltage distribution. When designing the power system, possibility of distribution generation and reverse power flow had not been considered. Therefore, renewable generation should be added to the distribution network adhering to the basic rules and limitations in order to secure the stability of the power system.

Let's look at the relationship between the active power, reactive power and voltage drop of the low voltage feeders.

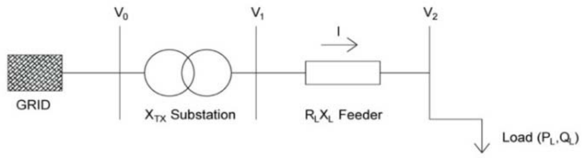

Fig. 3. Single line diagram of a simplified distribution line

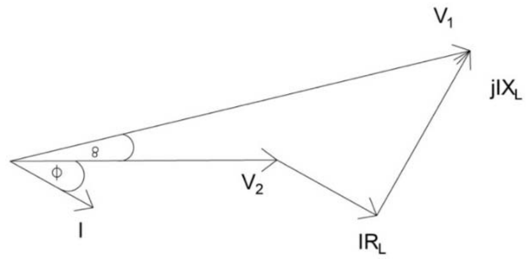

Fig. 4. Phasor diagram of the distribution line

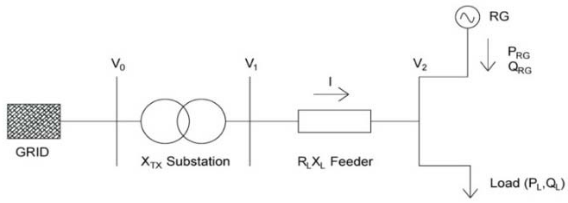

Fig. 5. Single line diagram with renewable generation

Where :

I : *Line Current*
P : *Net Active Power*
P_G : Active *Power Generated from Distributed Generators*
P_L : *Active Power consumed by Loads*
Q : *Net Reactive Power*
Q_G : *Reactive Power Generated from Distributed Generators*
Q_L : *Reactive Power consumed by Loads*
R_L : *Distribution Line Resistance*
V_0 : *Line Voltage of the Primary Side*
V_1 : *Line Voltage of the Secondary Side (Sending end)*
V_2 : *Line Voltage of the Receiving end*
ΔV : *Voltage Drop due to the Line Impedance*
X_L : *Distribution Line Reactance*
X_{TX} : *Transformer Reactance*
δ : *Load Angle*
φ : *Phase Angle Difference*

$$S = V_2 I^* \tag{1}$$

$$I = \frac{P - jQ}{V_2^*} \tag{2}$$

$$V_1 - V_2 = I\,(R_L + jX_L) \tag{3}$$

$$\Delta V = V_1 - V_2 = \frac{PR_L + QX_L}{V_2^*} + j\frac{PX_L - QR_L}{V_2^*} \tag{4}$$

Due to the small phase angle deviation in distribution networks, imaginary part of the above equation can be neglected. Therefore;

$$\Delta V = \frac{PR_L + QX_L}{V_2^*} \tag{5}$$

Here;

$$P = P_L - P_G \tag{6}$$

And

$$Q = Q_L - Q_G \tag{7}$$

Hence;

$$\Delta V = \frac{(P_L - P_G)R_L + (Q_L - Q_G)X_L}{V_2^*} \tag{8}$$

Here the receiving end voltage is taken as the reference. Therefore, the conjugate of the receiving end voltage is equal to itself. Thus;

$$\Delta V = \frac{(P_L - P_G)R_L + (Q_L - Q_G)X_L}{V_2} \tag{9}$$

By observing the above equation, dependency of voltage drop on the load and distributed generation, mainly renewables, can be analysed. Load power is proportional to the voltage drop while the renewable generation shows an inverse relationship. Therefore, it can be implied that the receiving end voltage increases with the renewable generation; whether it is either active power generation or reactive power generation. However, the R/X ratio of the distribution feeder is a significant factor in deciding the contribution of active and reactive power for voltage rise of the receiving end [7]. This gives rise to both the opportunities and challenges.

There are prevailing methods to mitigate the voltage related issues caused by solar photovoltaic generation in distribution feeders.

B. *Voltage Control Techniques*

Voltage control in transmission network is mainly achieved by controlling the reactive power due to the high reactance of the transmission network. However, in distribution networks both the active power and reactive power control methods can be used control the voltage since the distribution network is more resistive compared to the transmission network.

Reactive power support devices used in the distribution network consist of On Load Tap Changing transformers, capacitor banks, Energy Storage Systems and of FACTS (Flexible AC Transmission Systems) devices such as STATCOM (Static Synchronous Compensator), SVC (Static Var Compensator), and DVR (Dynamic Voltage Restoration) [4].

When it comes to voltage issues due to distributed generation caused by solar photovoltaics, voltage control can be achieved through local controls. Controllers used in solar photovoltaic inverters can be used to implement a control scheme through which the voltage is regulated. This may include both the active and reactive power control schemes. Reactive power control methods are elaborated in [4]. Use of cascade multilevel converters is another voltage and reactive power control technique which is gaining popularity. High frequency inverters and modern transformer-less inverters are being proposed to be used in voltage and reactive power control applications in solar photovoltaic systems.

Energy Storage Systems put together with solar photovoltaic systems are capable of providing a better voltage regulation and reactive power control [4]–[6]. As described under mathematical background, increasing distributed solar photovoltaic generation has been causing significant disturbances to the voltage regulation. Voltage rise due to high penetration is one of the concerning issues out of the lot. With the use of Energy Storage Systems such excess generation from the solar photovoltaic system can be stored rather than feeding it to the grid [6]. This may improve the distribution level voltage profile of the grid. However this should be carried out with reference to the load profile. Flow chart in the Fig.6. illustrates a possible control algorithm for dispatching Battery Storage based Solar PV system. It is developed considering the Sri Lankan distribution network.

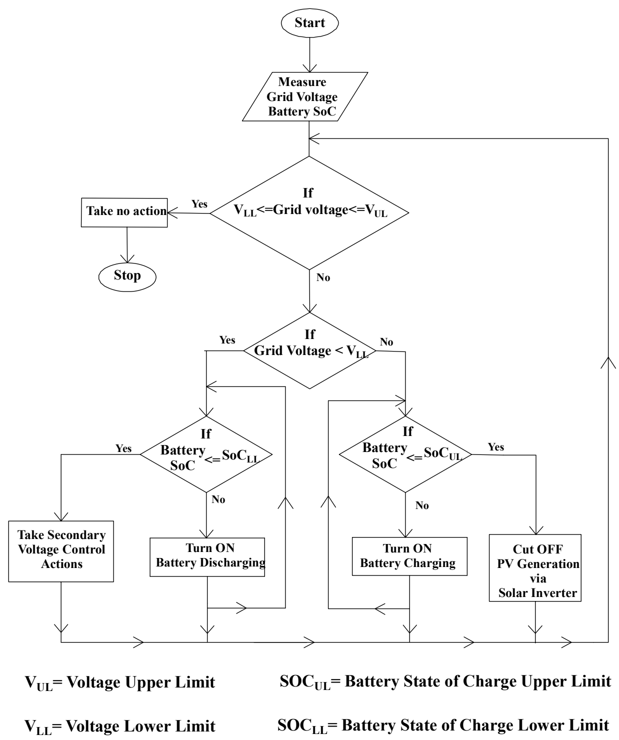

Fig. 6. Flowchart illustration of the control algorithm

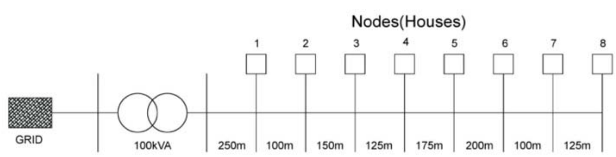

Fig. 7. Schematic diagram of the distribution line (rural scenario)

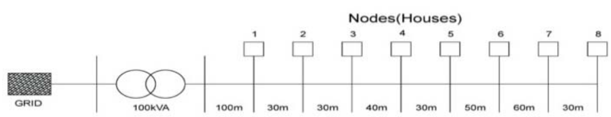

Fig. 8. Schematic diagram of the distribution line (urban scenario)

V. MODELING AND SIMULATION

Digsilent PowerFactory software was used to analyze the effect of distributed generation of solar photovoltaics in distribution feeders. Distribution feeder with eight nodes with line impedance of 0.5+j0.1 Ohm/km is used. Simulation was carried out for two main cases, which were subdivided into further six scenarios, which are tabulated in TABLE I, to get an overall view on the effectiveness of the ESS (Energy Storage System) on voltage regulation. Two main cases consist of an urban area and a rural area. Distance between the nodes were the main difference in each scenario. Schematic diagrams of the distribution line for each case are illustrated Fig.7 and Fig. 8.

Without ESS scenario was simulated without ESS support for nodes while with ESS scenario was simulated with 1 kW ESS support for each node. Loads connected each node is tabulated in TABLE II and TABLE III.

TABLE I. SUB SCENARIOS CONSIDERED IN SIMULATION

Scenario No	Description
1	High PV generation, Low domestic load – without ESS
2	High PV generation, Low domestic load – with ESS
3	Balanced – without ESS
4	Balanced – with ESS
5	Low PV generation, High domestic load – without ESS
6	Low PV generation, High domestic load – with ESS

TABLE II. URBAN SCENARIO

	Node	1	2	3	4	5	6	7	8
Scenario 1 & 2	***Load (kW)***	1	0.5	0.5	0.5	1	1	1	1
	PV (kW)	15	10	5	10	15	7	7	15
Scenario 3 & 4	***Load (kW)***	5	2	1.5	3	5	6	4	8
	PV (kW)	7	2.5	3	5	6	8	5	8
Scenario 5 & 6	***Load (kW)***	7	3	2	4	6	8	5	10
	PV (kW)	0	0	0	0	0	0	0	0

TABLE III. RURAL SCENARIO

	Node	1	2	3	4	5	6	7	8
Scenario 1 & 2	***Load (kW)***	1	0.5	0.5	0.5	1	1	1	1
	PV (kW)	7	5	2.4	5	7	3	3	7
Scenario 3 & 4	***Load (kW)***	5	3	2	3	5	2	2	5
	PV (kW)	7	5	2.4	5	7	3	3	7
Scenario 5 & 6	***Load (kW)***	5	3	2	3	5	2	2	5
	PV (kW)	0	0	0	0	0	0	0	0

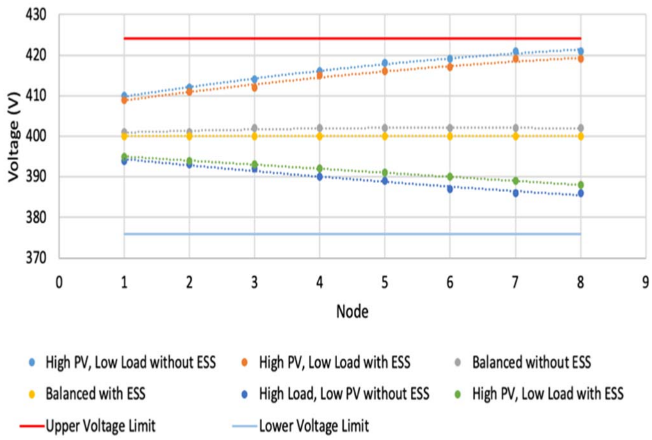

Fig. 9. Graph illustrating the voltage profile of the distribution line (urban scenario)

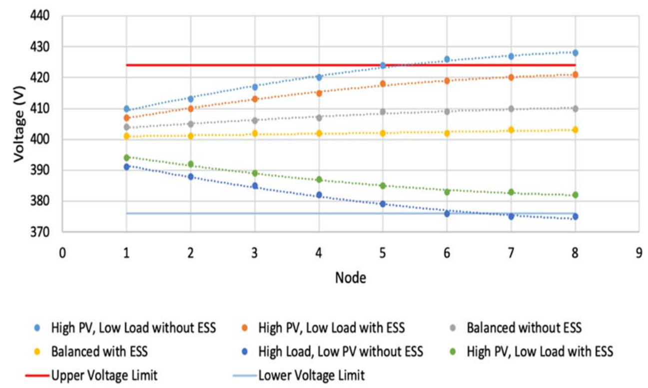

Fig. 10. Graph illustrating the voltage profile of the distribution network (rural scenario)

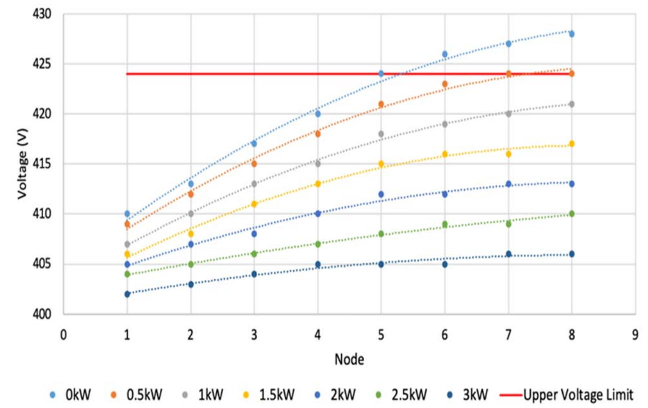

Fig. 11. Graph illustrating the effect of ESS capacity to the voltage profile of the distribution network

Furthermore, same simulation model was used to investigate the effect of the ESS for a selected case from the aforementioned scenarios. High PV generation and low domestic load scenario was simulated under varying ESS capacities. Starting from, without ESS support, ESS support for each node was increased in steps of 0.5 kW up to 3 kW per node. Diagram in the Fig. 12 shows the simulation model used.

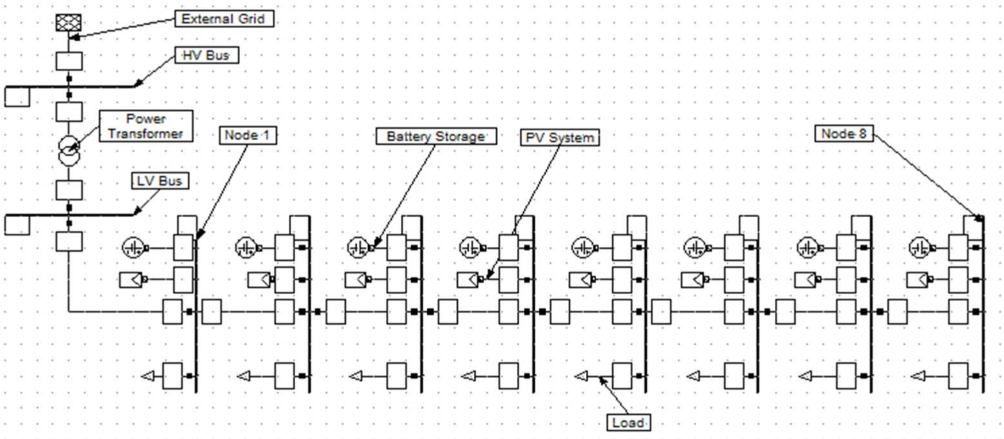

Fig. 12. Distribution line modeled using Digsilent PowerFactory software

VI. Simulation Results

Results obtained using the simulations are graphically illustrated in Fig. 9, Fig.10, and Fig. 11. Voltage profile improvements can be observed with the addition of ESS in both the urban and rural scenarios. In the urban scenario 1V to 2V improvement in each node was observed while voltage improvement in rural scenario was 5V to 6V which is more significant compared to the urban scenario. By increasing the ESS capacity, we could reduce the voltage rise significantly. Reduction of more than 7V (at the end node) per kW of ESS addition in each node was observed. This confirms that by increasing the ESS capacity, voltage profile of the distribution line can be improved significantly. However, a practically feasible value for the ESS should be selected considering the economics aspect as well.

VII. Conclusion

This paper proposed a battery storage system as a solution for the grid voltage violation in distribution network due to the high penetration of renewable energy. Proposed solution is verified through power flow simulations which showed conclusive evidence which support the claim that integrating a battery energy storage system with renewable generators such as solar photovoltaic systems can mitigate the voltage violations. According to the simulation results, effect of the Battery Energy Storage Systems were more effective in rural distribution feeder which suggests when the line impedance is high. Batteries are necessary to keep the voltage rise and fall within limits without any curtailment of renewable power generation and domestic loads. Financial and Economic analysis should be carried out as the technical feasibility alone would not be sufficient to practically implement the system. Tariff scheme which provides incentives to the customers considering both the active and reactive power export, should also be implemented. These aspects are to be looked at in future work.

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