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Increasing Distribution Grid Hosting Capacity Through Wire And Non-Wire Solutions

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Increased deployment of distributed generation (DG) can adversely impact the operational performance of distribution networks. This increment can potentially change network power flow and result in several operational issues such as reduced power quality, overvoltage, and ineffective protection. In order to quantify the degradation bounds of distribution operation due to increasing DG integration, the concept of hosting capacity is introduced. The aim of this thesis is to increase the DG hosting capacity in distribution network by proposing several wire and non-wire solutions. To this end, these solutions include network reconfiguration, reactive power control, and energy storage system deployment. The network reconfiguration can change the power flow in the system while the reactive power control can decrease the voltage rise and power loss in the system, which lead to increase in hosting capacity. The energy storage systems can be utilized to locally capture DG generation, which leads to an increase in the hosting capacity. This thesis introduces an optimization- based hosting capacity method developed based on a linear power flow model to optimally determine DGs hosting capacity. Numerical simulations on a radial distribution test system illustrate the effectiveness of the proposed solutions.

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INCREASING DISTRIBUTION GRID HOSTING CAPACITY THROUGH WIRE AND NON-WIRE SOLUTIONS

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Abstract

Increased deployment of distributed generation (DG) can adversely impact the operational performance of distribution networks. This increment can potentially change network power flow and result in several operational issues such as reduced power quality, overvoltage, and ineffective protection. In order to quantify the degradation bounds of distribution operation due to increasing DG integration, the concept of hosting capacity is introduced. The aim of this thesis is to increase the DG hosting capacity in distribution network by proposing several wire and non-wire solutions. To this end, these solutions include network reconfiguration, reactive power control, and energy storage system deployment. The network reconfiguration can change the power flow in the system while the reactive power control can decrease the voltage rise and power loss in the system, which lead to increase in hosting capacity. The energy storage systems can be utilized to locally capture DG generation, which leads to an increase in the hosting capacity. This thesis introduces an optimization-based hosting capacity method developed based on a linear power flow model to optimally determine DGs hosting capacity. Numerical simulations on a radial distribution test system illustrate the effectiveness of the proposed solutions.

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List of Abbreviations

DER	Distributed Energy Resource
DG	Distributed Generation
DSO	Distribution System Operator
LP	Linear Programming
MIP	Mixed-Integer Programming
POI	Point of Interconnection
PV	Photovoltaic
ESS	Energy storage system
SVC	Static VAR compensator

Nomenclature

Indices

c	Index for points of interconnection
m,n,i	Index for buses
$\wedge$	Index for calculated variables

Sets

B	Set of buses
C_m	Set of points of interconnection connected to bus *m*
L	Set of lines
L_m	Set of lines connected to bus *m*
Γ	Set of Loops

Parameters

b_{mn}	Susceptance of line *mn*
g_{mn}	Conductance of line *mn*
M	Large positive number
D	ESS depth of discharge
E_m^{max}	Maximum energy capacity of ESS
$P_m^{D,min}$	Lower limit of real load at bus *m*
$P_m^{D,max}$	Upper limit of real load at bus *m*
P_c^{max}	Maximum real power exchange with upstream grid at point of interconnection *c*
PL_{mn}^{max}	Maximum real power flow of line *mn*
$Q_m^{D,min}$	Lower limit of reactive load at bus *m*
$Q_m^{D,max}$	Upper limit of reactive load at bus *m*

Q_c^{max}	Maximum reactive power exchange with upstream grid at point of interconnection *c*
$Q_m^{SVC,max}$	Upper limit of reactive power from SVC at bus *m*
QL_{mn}^{max}	Maximum reactive power flow of line *mn*
r_{mn}	Resistance of line *mn*
x_{mn}	Reactance of line *mn*
ΔV_m^{min}	Lower limit of voltage magnitude deviation in bus *m*
ΔV_m^{max}	Upper limit of voltage magnitude deviation in bus *m*
$\propto_m$	Reactive power ratio at bus *m*
η	DES efficiency

Variables

P_m	Real power injection at bus m
P_m^D	Real load at bus m
P_m^G	Real power of distributed generation at bus m
P_c	Real power exchange with upstream grid at point of interconnection c
E_m	ESS stored energy
P_m^{ESS}	Real power of energy storage system at bus m
PL_{mn}	Real power flow at line mn
PL_{mn}^{loss}	Real power loss of line mn
Q_m	Reactive power injection at bus m
Q_m^D	Reactive load at bus m
Q_m^G	Reactive power of distributed generation at bus m
Q_m^{SVC}	Reactive power of static VAR compensator at bus m

Q_c	Reactive power exchange with upstream grid at point of interconnection c
QL_{mn}	Reactive power flow at line mn
QL_{mn}^{loss}	Reactive power loss of line mn
V_m	Voltage magnitude at bus m.
z_{mn}	Status indicator of line mn
θ_m	Voltage angle at bus m
ΔV_m	Voltage magnitude deviation at bus m
$\Delta\theta_m$	Voltage angle deviation at bus m

Chapter One: Introduction

1.1. Power system delivery

The traditional way of electricity production is one-way power flow. Power is generated at generation stations then transmitted to customers through long transmission lines. The process of power system delivery passes into four stages as shown in Figure 1.1.

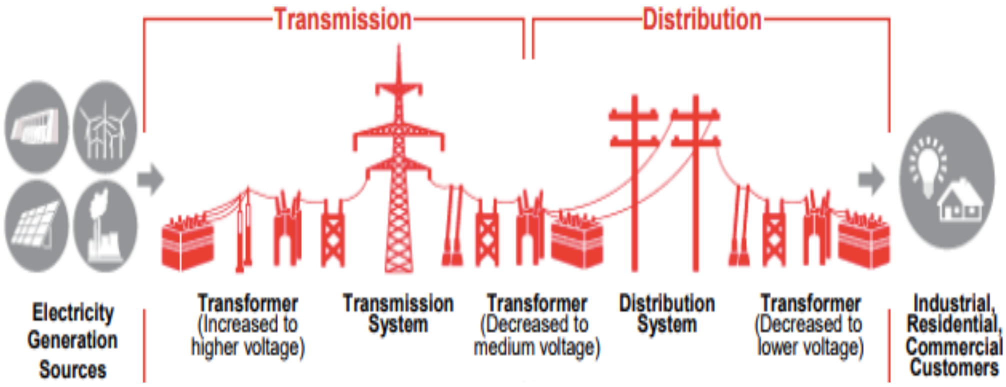

Figure 1.1: The Traditional Power System Delivery [1].

The increased deployment of distributed energy resources (DERs), which are mainly deployed by end-use customers and connected to distribution networks, is changing the traditional practice in managing the power system. This change leads to high investments in research and development to not only meet the system needs, but also to introduce innovative solutions. Power is generated at customers' premises is known as distributed generation (DG) and the customers will be prosumers. The prosumers are costumers who can produce and consume energy. The amount of electricity at distribution level ranges from 100 kW to 1 MW. DG introduces several benefits for utilities as well as consumers. In terms of utilities, small amount of power improves overall efficiency, enhance resiliency, reduce losses and most importantly defer transmission lines upgrade. From consumers' point of view, less power interruption, sustainable solutions, and economic benefits are main advantages for deploying DG.

However, the increased DGs deployment comes with challenges for changing the power flow and that would introduce issues to power system ranging from technical to regulations as shown in Figure 1.2. The most significant technical problem is voltage fluctuation. Another technical issue is protection. The bidirectional power flow makes protection scheme does not work in proper manner since it is not designed to work in such power flow as shown in Figure 1.3. Moreover, market and policies cause critical issues for DG deployment, but these issues are not discussed in this thesis. DGs technologies appear in many forms such as photovoltaic system, wind turbine, synchronous and induction generators, full cell, etc.

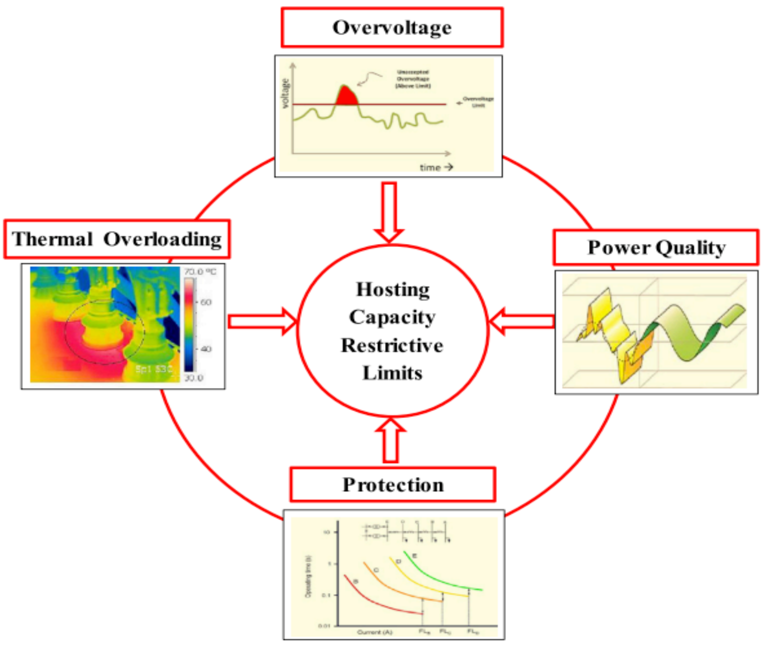

Figure 1.2: Parameters that can be considered in hosting capacity calculation [2].

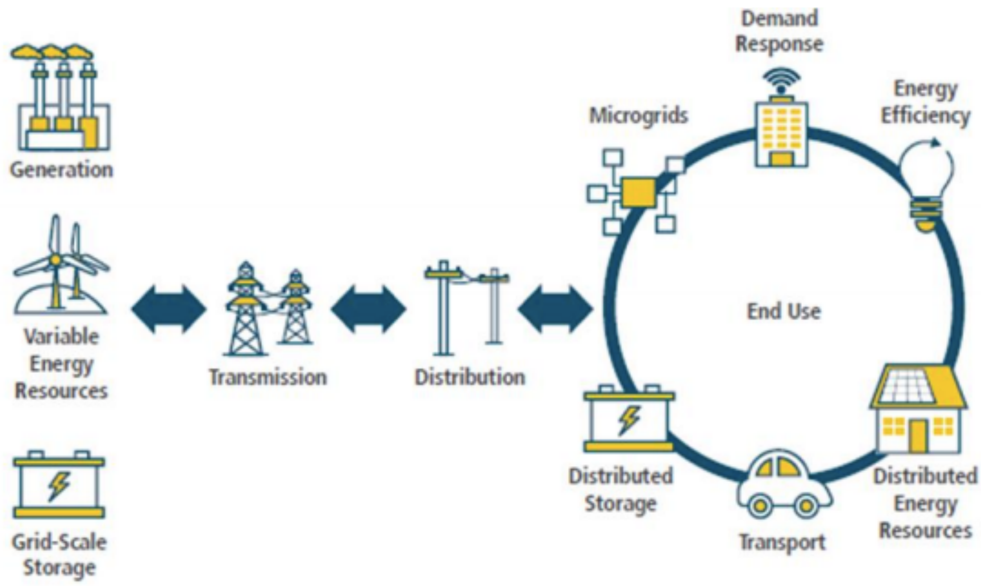

Figure 1.3: The Two Way Power System Delivery [3].

1.2. Hosting Capacity

There has been a strong drive in the past decade to increase the integration of renewable DGs in distribution networks [4]. Particularly common are end-user deployments of solar photovoltaics (PV) and wind turbines as illustrated in Figure 1.4. Such technologies have the potential to solve long-term environmental and economic concerns by reducing greenhouse gas emissions, power generation costs, and detrimental reliance on fossil fuels [5]. However, excessive integration of DGs into distribution grids is operationally problematic. Power injections from DGs may, at some times, drastically change distribution operating conditions. Adverse side-effects such as voltage fluctuations, thermal overloads, and overburdening components not inherently designed to support two-way power flows are some of the potential drawbacks of increased DGs penetration in distribution networks [6]. These challenges must be overcome to unleash the full benefits of DGs integration.

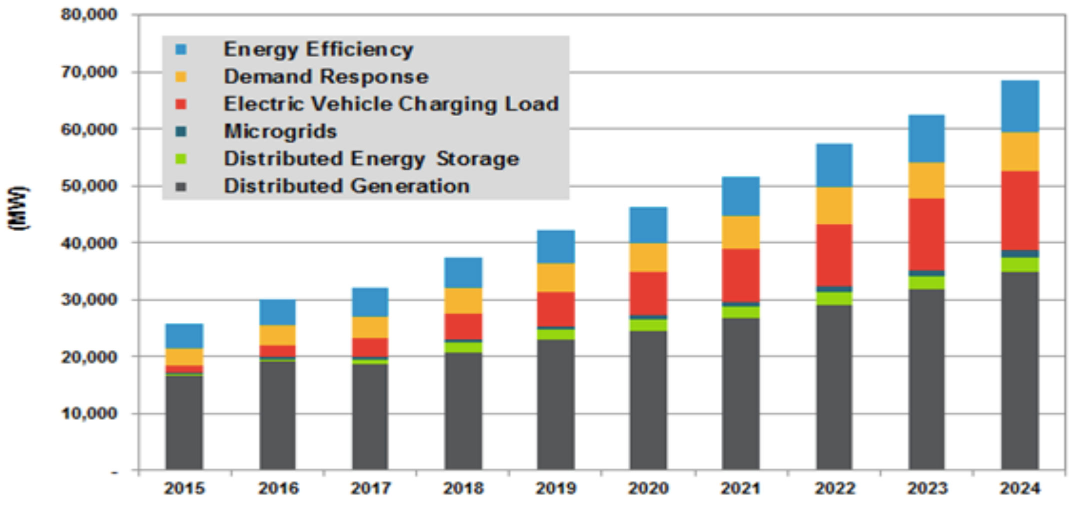

Figure 1.4: Annual Installed DER Power Capacity Additions by DER Technology [7].

One approach to accommodate additional DGs capacities in distribution networks is through infrastructural upgrades. In addition to not being adaptive to short-term demands, such upgrades often turn out to be excessively costly. An alternative approach is to quantify the network hosting capacity and then ensure that DG allocation does not exceed that capacity as shown in Figure 1.5. Such a scheme allows network operators to take full advantage of existing infrastructure and postpone costly upgrades[8], while still allowing for future upgrades, if it is needed. The latter approach requires an appropriate hosting capacity analysis to assess the network capability [9], [10].

This thesis focuses on three strategies to increase hosting capacity, namely network reconfiguration, reactive power control, and energy storage system (ESS) deployment. These strategies ultimately address previously mentioned challenges including those of overload and voltage fluctuation [11], [12]. Distribution hosting capacity calculations determine the amount of additional generation and load which can be added to the grid without requiring any upgrades.

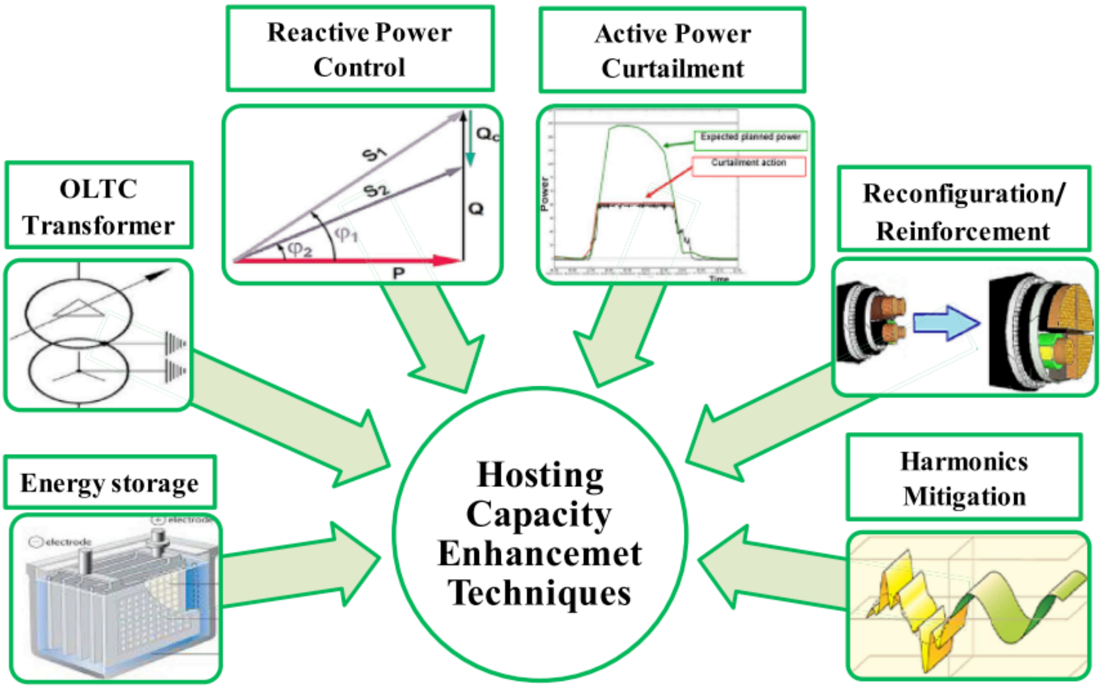

Figure 1.5: Increasing hosting capacity techniques [2].

1.3. Network reconfiguration

The reconfiguration of a distribution grid is accomplished by changing the state of switches in the grid. Since we wish to maintain radial network operation, reconfiguring the network must not affect its radiality structure. The word “radial” here refers to a configuration that connects all nodes but does not contain connected loops. The radiality condition is forced by verifying that the total number of lines comprising the loop is greater than the number of closed lines in all potential loops. That means there is at least one line in every loop should be opened.

1.4. Reactive power control

An injection of DGs can result in significant increases in the voltage magnitudes of other buses accommodating DGs. Increasing the DGs power can also increase reverse power flow, which can cause an over-voltage at the DGs location. The objective of the proposed method is to address the problem of voltage regulation in active distribution networks with a high level of DGs integration; specifically, the focus is on managing voltage variability across the network due to the uncontrolled changes in the generated power by DGs. Thus, Reactive power control (RPC) is applied to the system to mitigate the rise in voltage magnitude, and that may increase the distribution grid hosting capacity. The RPC function is depending on the R/X ratio of lines where the higher R/X ratio, the smaller is the effect of RPC. Therefore, Static Var Compensator (SVC) is used to maintain voltages deviations within limits.

1.5. Energy storage system

The nature of intermittency in renewable energy is a critical limiter to increase the amount of renewable energy penetration into the grid. The emerge of ESSs offer tremendous benefits for both utilities and individuals including economic, environment, technical, etc. [13]. In terms of utilities, meeting the peak demand is a critical impediment; thus, ESSs not only helps meeting peak demand but also provides ancillary services such as frequency regulation. Another great benefit of utilizing ESSs is greenhouse gas reduction as well as increased the distributed generation. Deferring grid upgrade and build new transmission is an economic advantage of deploying ESSs. Individuals, on the other hand, can get benefit from deploying ESSs. They can have a reliable and efficient energy source without power interruption. Further, ESSs introduce opportunities for individuals to participate in power energy systems.

Chapter Two: State of the Art in Distribution Grid Hosting Capacity

2.1 High DG penetration impact

The high distribution energy resources penetrations have negative impacts on the distribution system. In [14], voltage and protection issues are some of the DG penetration impacts that have been discussed. It is concluded that not all these problems will happen with low DG penetration, but all these issues should be considered when designing a network to ensure system reliability. In [15], not only voltage and protection issues but also the reverse power flow that occurs due to the high DG penetration during the low load is presented. Moreover, overvoltage and voltage unbalance are caused by the integration of small DG units into one phase in low voltage (LV) distribution network is discussed in [16]. The author concludes that overvoltage and unbalanced voltage are not only caused by the high DG penetration but also by their placement along with the three phases.

2.2 Hosting capacity calculation

In this section, a variety of studies that compute the grid hosting capacity with various considerations are listed first followed by additional research that focuses on increasing the hosting capacity. The work in [17], uses a scenario-based stochastic analysis to calculate grid hosting capacity. The method uses OpenDSS [18] to calculate power flows and discusses impact of PV locations on voltage quality. OpenDSS is also used in [19] for a similar calculation. A more streamlined and detailed hosting capacity analysis is provided in [20] which considers voltage, thermal, and protection issues suitable for commercial software. The study in [21] poses that realistic network measurements result in a higher hosting capacity compared to considering worst-case scenarios.

In order to increase the hosting capacity, reactive power capability of PV inverters and capacitor banks jointly with cable reinforcement techniques are leveraged in [22] using MATPOWER for power flow calculations. Authors [23] also examines PV inverters to improve PV hosting capacity by deploying a local Volt-Var droop control. Moreover, [24] demonstrates by field experiments that reactive power control of PV inverters can be utilized for static voltage support and can increase PV hosting capacity. All the aforementioned works do not consider SVCs, network reconfiguration, or ESSs to increase hosting capacity.

2.3 Increasing the hosting capacity

Recently, researchers and DSOs are more interested in increasing DGs hosting capacity without upgrading or reinforcing the grid. Therefore, a variety of approaches in increasing the hosting capacity are introduced in the literature; however, their effectiveness depends on the grid parameters and the DSOs preference. The study in [25] uses network reconfiguration and DG placement to maximize grid hosting capacity. Power flows are convexified similar to [23] and [24] to determine a tractable optimal DG placement problem. A scalable combinatorial enumeration technique is utilized to determine several optimal network configurations for distribution system operators (DSOs). In [28], an adjusting network reconfiguration and a power electronic device, called soft open point that can control active and reactive flows from adjacent feeders, are used to maximize grid hosting capacity. A combination of heuristic methods is used to solve the combined problem with worst-case load. In [29], a multiperiod OPF method for determining the DG penetration enhancement in distribution networks by using static and dynamic network reconfiguration is proposed. The static network reconfiguration considers remotely and manually controlled switches while the dynamic network reconfiguration considers the remotely controlled switches only. The problem is posed as a mix-integer nonlinear programming. In addition in [30], optimal network reconfiguration and DG allocation are utilized to maximize grid hosting capacity. A linearized AC power flow equation is developed based on a set of assumptions. The problem is formulated as MILP with a proper radiality constraints. Finally, these works do not consider SVC or batteries.

The work in [12] uses on-load tap changer and SVCs to maximize grid hosting capacity robust to uncertainty in power generation. They linearize the DistFlow equations [31] to make the problem tractable and achieve an MILP formulation. The study in [32] determines size and location of ESSs jointly with capacitor banks and network reinforcement. A piece-wise linearization method for the power flows is utilized to arrive at a mixed-integer linear programming formulation. SVCs and network reconfiguration are not utilized in this study. Studies in [30] and [31] focus on a multi-stage formulation for optimal timing, sizing, and placement of DGs, ESSs and capacitor banks. A linearization technique is proposed for loss calculations and the formulation is a MILP. Nevertheless, network reconfiguration is not considered in this work. In [35], A droop-like control for battery setpoints is proposed based on voltage sensitivity calculations so that overvoltage does not occur and PV hosting capacity is increased. The setpoints are calculated using linear programming. This work considers neither network reconfiguration nor SVCs.

Chapter Three: Model Outline

The present thesis focuses on the development of linearized mathematical models to determine the optimal network reconfiguration, the optimal size of SVC, and the optimal size of ESS to maximize the DG hosting capacity. The hosting capacity optimization problem is formulated as a mixed-integer linear program (MILP). In order to mitigate the effect of voltage deviations on the hosting capacity, the use of voltage regulation is considered to ensure that the increase in grid hosting capacity does not violate acceptable voltage limits. Unlike existing studies on increasing available grid hosting capacity, this thesis leverages a novel power flow linearization developed in our previous work [36]. This can speed-up the hosting capacity optimization problem while taking into consideration the interdependency of network reconfiguration and the optimal size for SVCs and ESSs, and sizing and locations for DGs.

Distribution networks are typically designed as passive networks operating with a radial structure. This specific design offers simple operation and maintenance at low costs [37]. In this architecture, switches can be added to connect/disconnect nodes in the system. Distribution network switches are categorized either as sectionalizing switches or tie switches. During normal operation, the former are typically closed, and the latter are open. Network topology may be modified by changing the status of these switches. This practice is known as network reconfiguration and is commonly utilized during emergency operations. Reconfiguration has also been applied to reduce power losses, balance system loads, improve voltage levels, and restore electricity services

[37]. In a previous study [30], our group proposed optimal network reconfiguration and DG allocation to maximize grid hosting capacity using a MILP formulation. Albeit, [30] ignores SVCs and ESSs.

DG incorporation could cause undesirable fluctuations in the voltage profile of a distribution system due to uncontrolled variations in power generation and accordingly net consumption [38]. A major challenge that distribution system operators are facing when incorporating DGs is therefore maintaining the voltage within desired levels throughout the network. Reactive power control is defined as the process of managing voltage levels and reactive power to achieve operation objectives without violating operating constraints [39]. SVCs can be used to reduce active power loss, reduce reactive power flows, and reduce voltage deviations. An advanced technique to improve DG hosting capacity involves allowing DGs to regulate feeder voltages to actively cope with the fluctuations. Reactive power control can be implemented using such distributed control, obviating the need for advanced communications technology [40]. This improves system reliability and speeds up decision making; however, it increases the complexity of the distribution system as it introduces numerous local controllers to the system.

ESSs may be utilized to overcome the intermittency of solar energy as well as increase system reliability. Additionally, storage technologies help in overcoming the overvoltage issues resulting from high DG integration. Energy storage technologies, therefore, offer a solution to increase the available grid hosting capacity. Different kinds of energy storage technologies can be used, each with their own benefits useful for tackling different technical problems. If both ESSs and high levels of DG are optimally placed in distribution networks, they can reduce transmission and distribution loss, regulate voltages, delay costly upgrades, reduce peak demand, and improve power quality. In this thesis, the effect of a general battery storage system is also considered.

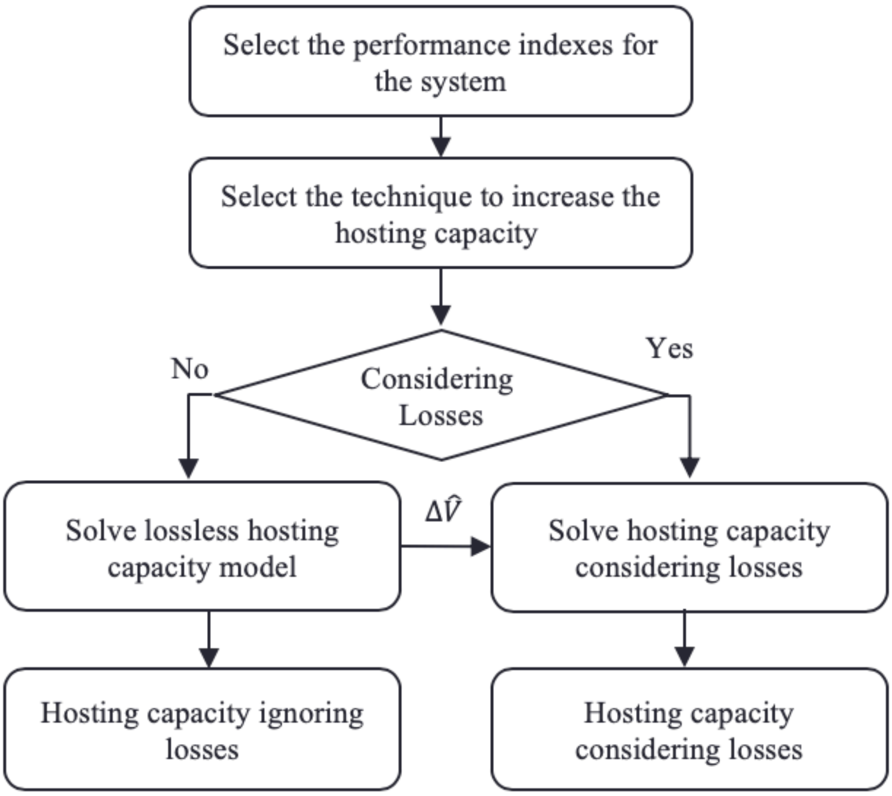

Figure 3.1: Flow chart of the hosting capacity calculation method.

3.1 Problem Formulation

An optimization-based method is proposed with the goal of evaluating strategies aimed at increasing the DG hosting capacity. This objective is achieved by using linearized AC power flow equations to find the maximum amount of DG which can be incorporated into a given radial distribution network without exceeding operational limits. The linearized power flow model is used to find the optimal hosting capacity by simultaneously optimizing DG profile, distribution network reconfiguration, and SVC and ESS sizes.

3.1.1 Power Flow Linearization

The employed power flow model uses the point of interconnection (POI), i.e., the point where the distribution network is connected to the upstream system, as a reference. The POI voltage is assumed to be $1\angle 0$ p.u. and is used to redefine the voltage magnitude and phase angle (V_m and θ_m) for all network buses. Bus m voltage deviation (ΔV_m and $\Delta\theta_m$) are defined as the difference of the bus voltage magnitude and phase angle from the corresponding quantities at POI. The redefined voltage magnitudes and angles for all downstream buses are thus expressed as:

$$V_m = 1 + \Delta V_m \qquad \forall m \in B \qquad (1)$$

$$\theta_m = 0 + \Delta\theta_m \qquad \forall m \in B \qquad (2)$$

Two assumptions are made to simplify the power flow equations. First, the trigonometric terms of two connected buses are simplified using small angle approximations, i.e., $\sin(\theta m\text{-}\theta n) \approx (\Delta\theta m \text{ -}\Delta\theta m)$ and $\cos(\theta m\text{-}\theta n)\approx 1$ are employed. Second, any term involving the product of voltage magnitude deviations and voltage angle deviations is ignored. Based on these assumptions, the simplified real and reactive power flow equations are obtained as follows:

$$PL_{mn} = g_{mn}(1 + \hat{\Delta V})(\Delta V_m - \Delta V_n) - b_{mn}(\Delta\theta_m - \Delta\theta_n) \qquad \forall mn \in L \qquad (3)$$

$$QL_{mn} = -b_{mn}(1 + \hat{\Delta V})(\Delta V_m - \Delta V_n) - g_{mn}(\Delta\theta_m - \Delta\theta_n) \qquad \forall mn \in L \qquad (4)$$

The values of $\hat{\Delta V}$ in (3) and (4) are specific constants that are determined by pre-solving a set of linearized line flows as illustrated in Figure 3.1. See [36] for a detailed derivation.

3.1.2 SVC Limits

SVCs are used to aid voltage regulation. Constraint (5) expresses the capability limits of SVC:

$$-Q_{m}^{SVC,max} \leq Q_{m}^{SVC} \leq Q_{m}^{SVC,max} \qquad \forall m \in B \qquad (5)$$

3.1.3 Maintaining Radiality During Reconfiguration

The reconfiguration of a distribution grid is accomplished by changing the state of switches in the grid. Since we wish to maintain radial network operation, reconfiguring the network must not affect its radiality structure. The word "radial" here refers to a configuration that connects all nodes but does not contain connected loops. The radiality condition is forced by verifying that the total number of lines comprising the loop is greater than the number of closed lines in all potential loops. That means there is at least one line in every loop should be opened. The radiality constraint is mathematically described as follows:

$$\sum_{mn \in \Gamma} z_{mn} \leq L_{mn} - 1 \qquad \forall mn \in L \qquad (6)$$

Here, Γ is the set of all possible loops, L_{mn} is the total number of lines in each loop, and z_{mn} is the binary variable that denotes the status of the line connecting buses *m* and *n*. If the line switches are opened, the value of z_{mn} is 0 and if the switches are closed, z_{mn} value is 1.

3.1.4 Energy Storage

The operation of ESS is modeled as follows:

$$P_{m}^{ESS} = P_{m}^{ESS,dis} + P_{m}^{ESS,ch} \qquad \forall m \in B \qquad (7)$$

$$0 \leq P_{m}^{ESS,dis} \leq P_{m}^{ESS,max} u_{m} \qquad \forall m \in B \qquad (8)$$

$$-P_{m}^{ESS,max}(1 - u_{m}) \leq P_{m}^{ESS,ch} \leq 0 \qquad \forall m \in B \qquad (9)$$

$$E_{m} = E_{m(t-1)} - \frac{P_{m}^{dis}}{\eta_{m}} - P_{m}^{ch} \qquad \forall m \in B \qquad (10)$$

$$(1-D)E_m^{max} \le E_m \le E_m^{max} \qquad \forall m \in B \qquad (11)$$

Here, P_m^{ESS} (7) is the summation of charging and discharging powers drawn by ESS in bus m. The output is positive when the ESS is charging, and it is negative when the ESS is discharging. In (8) and (9)$P_m^{ESS,ch}$ and $P_m^{ESS,dis}$ are respectively the amount of power drawn due to charging and discharging. The binary variable u_m represents the charging/discharging status of the ESS. Using u_m ensures that the ESS is either charging or discharging and never both at the same time. When u_m is set to 1, the ESS is discharging, and when u_m is set to 0, the ESS is discharging. The ESS stored energy is determined in (10) as the earlier hour stored energy minus the discharged or the charged power; thus, the stored energy will rise if the ESS is charging and it will drop if the ESS is discharging. (11) limits the stored energy by considering the ESS depth of discharge.

3.1.5 Hosting Capacity Optimization Model

The grid hosting optimization problem is given next:

$$\max \textstyle\sum_{m \in B} P_m^G \qquad (12)$$

$$\textstyle\sum_{c \in C_m} P_c + \sum_{n \in L_m} PL_{mn} + P_m^G + P_m^{ESS} = P_m^D \qquad \forall m \in B \qquad (13)$$

$$\textstyle\sum_{c \in C_m} Q_c + \sum_{n \in L_m} QL_{mn} + Q_m^G + Q_m^{SVC} = Q_m^D \qquad \forall m \in B \qquad (14)$$

$$\textstyle\sum_{mn \in \Gamma} z_{mn} \le L_{mn} - 1 \qquad \gamma \in \Gamma \qquad (15)$$

$$P_m^{ESS} = P_m^{ESS,dis} + P_m^{ESS,ch} \qquad \forall m \in B \qquad (16)$$

$$0 \le P_m^{ESS,dis} \le P_m^{ESS,max} u_m \qquad \forall m \in B \qquad (17)$$

$$-P_m^{ESS,max}(1-u_m) \le P_m^{ESS,ch} \le 0 \qquad \forall m \in B \qquad (18)$$

$$E_m = E_{m(t-1)} - \frac{P_m^{dis}}{\eta_m} - P_m^{ch} \qquad \forall m \in B \qquad (19)$$

$$(1-D)E_m^{max} \le E_m \le E_m^{max} \qquad \forall m \in B \qquad (20)$$

$$-M(1-z_{mn}) \le PL_{mn} - \left(g_{mn}(1+\hat{\Delta V})(\Delta V_m - \Delta V_n) - b_{mn}(\Delta\theta_m - \Delta\theta_n)\right) \le M(1-z_{mn}) \qquad (21)$$

$$-M(1-z_{mn}) \le QL_{mn} - \left(-b_{mn}(1+\hat{\Delta V})(\Delta V_m - \Delta V_n) - g_{mn}(\Delta\theta_m - \Delta\theta_n)\right) \le M(1-z_{mn}) \qquad (22)$$

$$-P_m^G *\propto \leq Q_m^G \leq P_m^G *\propto \qquad \forall m \in B \qquad (23)$$

$$-Q_m^{SVC,max} \leq Q_m^{SVC} \leq Q_m^{SVC,max} \qquad \forall m \in B \qquad (24)$$

$$-P_m^{c,max} \leq P_m^c \leq P_m^{c,max} \qquad \forall c \in C \qquad (25)$$

$$-Q_m^{c,max} \leq Q_m^c \leq Q_m^{c,max} \qquad \forall c \in C \qquad (26)$$

$$-z_{mn}PL_{mn}^{max} \leq PL_{mn} \leq z_{mn}PL_{mn}^{max} \qquad \forall mn \in L \qquad (27)$$

$$-z_{mn}QL_{mn}^{max} \leq QL_{mn} \leq z_{mn}QL_{mn}^{max} \qquad \forall mn \in L \qquad (28)$$

$$\Delta V_m^{min} \leq \Delta V_m \leq \Delta V_m^{max} \qquad \forall m \in B \qquad (29)$$

Equation (12) denotes the objective which is the summation of installed DG capacity in allowable buses. Equations (13) and (14) are the real and reactive power balance equations that ensure at each bus the total real and reactive power supplied from DGs, ESSs, SVCs, and the flows to neighboring buses equals the power demand at that bus. The ESSs are not considered to supply reactive power, hence, the reactive power injection from ESSs do not appear in (14). Radiality as formulated in (15) is used to confine network reconfiguration to radial structures only. Conditions relating to the ESSs operation outlined in the previous subsection are also incorporated into the optimization as formulated by (16)-(20). Constraints (21) and (22) are the linearized real and reactive power flow equations, with the reconfiguration binary variable z_{mn} acting to switch open and close the lines. Constraints (23) and (24) present the DG reactive power limit and the limit of SVC. The real and reactive power consumptions are limited by (25) and (26). Equations (27) and (28) restrict the line real and reactive power limits. Finally, (29) enforces voltage limits.

Chapter Four: Numerical Simulation

The proposed formulation is applied to the IEEE 33-bus distribution test system. The modeled network comprises 32 lines and 5 tie switches as shown in Figure 4.1. It should be mentioned that SVCs and ESSs optimal placement are not considered in this work. Thus, 2 SVCs and 2 ESSs are randomly placed.

There are 5 loops in the system, and they occur when the 5 tie switches are closed as illustrated in Table 4.1. The maximum capacity for each ESS is set to 1000 kW. The total base load is fixed at 3.715+j2.3 MVA and a 0.8 lagging power factor is considered while the maximum power exchange with the upstream grid is set at 4.6 MW.

Lower and upper voltage limits are respectively fixed at 0.9 and 1.1 pu. The proposed model is modeled by GAMS and solved using CPLEX 12.6 [41] in a MacBook Air with a 1.6 GHz Intel Core i5 processor.

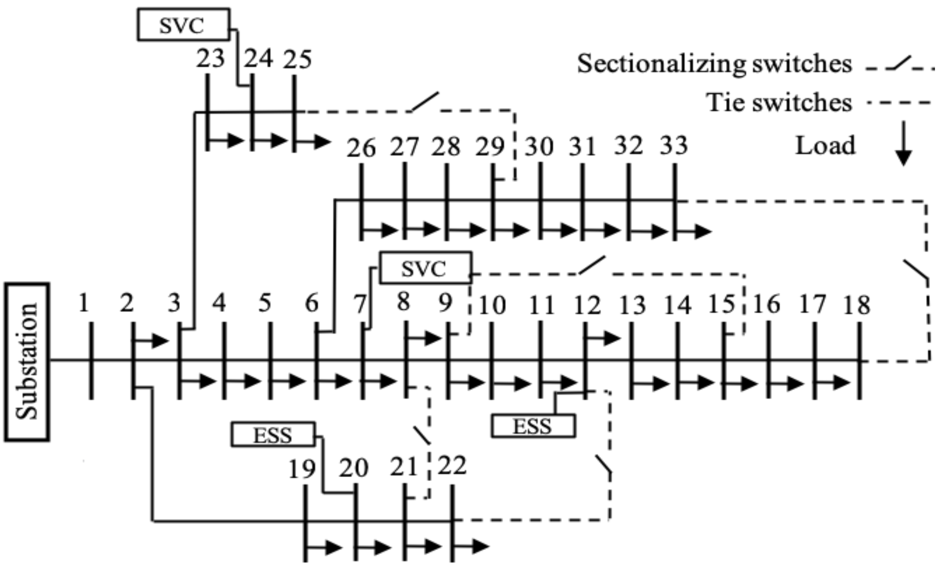

Figure 4.1: IEEE 33 bus distribution test system[30].

Table 4.1: All possible loops generated by closing tie lines [30].

Loop #	Lines making the loop
1	9, 10, 11, 12, 13, 14, 34
2	6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 25, 26, 27, 28, 29, 30, 31, 32, 36
3	3, 4, 5, 22, 23, 24, 25, 26, 27, 28, 37
4	2, 3, 4, 5, 6, 7, 18, 19, 20, 33
5	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 18, 19, 20, 21, 35

The following cases are considered:

Case 0: Optimal hosting capacity as a base model.

Case 1: Optimal hosting capacity with SVCs.

Case 2: Optimal hosting capacity with network reconfiguration.

Case 3: Optimal hosting capacity with ESSs.

Case 4: Optimal hosting capacity with network reconfiguration, ESSs, and SVCs.

Case 5: Sensitivity analysis of hosting capacity with respect to the line limits.

Two scenarios are considered for each case, in which in scenario 1, DGs are allowed to be installed at all buses at the same time while in scenario 2, DGs are installed at end buses only.

4.1 Case 0: Optimal hosting capacity as a base model

The hosting capacity calculation of the IEEE 33-bus is determined with an optimal solution without utilizing the aid of reconfiguration, ESSs, or SVCs. The results of Case 0 are laid out in Table 4.2. The table illustrates power exchanges with the grid, DGs power injection, line power losses, and voltage magnitude range for each scenario. In scenario 1, the total hosting capacity is 8450.6 kW. An amount of 4588 kW is transferred to the main grid while the rest is consumed by local loads. The power loss is 147.6 kW and bus voltages vary between 0.99 and 1.06.

In scenario 2, the hosting capacity calculation of the IEEE 33-bus is optimized where the DGs are installed only at end buses. As shown in Table 4.2, the total hosting capacity for this scenario is 1470 kW, with injections at buses 18, 22, 25 and 33. Bus25 hosts the most generated power with a value of 920 kW. The power transferred from the main grid is 2363.7 kW. Incurred power losses are at 118.7 kW.

Table 4.2: The result for Case 0.

Scenario #	Scenario 1	Scenario 2
Total DG (kW)	8450.6	1470.0
Power Exchange (kW)	- 4588	2363.7
Total loss (kW)	147.6	118.7
Voltage (p.u.)	0.99-1.06	0.93-1.00

4.2 Case 1: Optimal hosting capacity with SVC

In this case, SVCs are used as a technique to control voltage rise in the system, which leads to an increase in the DG hosting capacity. Two SVCs are placed in bus 7 and 24 to compensate the need for reactive power in these buses. The results are tabulated in Table 4.3. In scenario 1, the DG hosting capacity has increased slightly by using SVCs when it is compared to Case 0. Moreover, the voltage magnitude falls between the acceptable limits as shown in Figure 4.2. However, in the second scenario the DG hosting capacity has not changed, which is due to the capacity of the lines connected to the end buses. The results show that SVCs may not significantly enhance the hosting capacity as the line capacity is typically a more limiting factor.

Table 4.3: The result for Case 1.

Scenario #	Scenario 1	Scenario 2
Total DG (kW)	8456	1470
Power Exchange (kW)	-4588	2377.8
Total loss (kW)	152.2	132.8
Voltage (p.u.)	0.99-1.05	0.92-1.00
SVC location	7 and 24	7 and 24

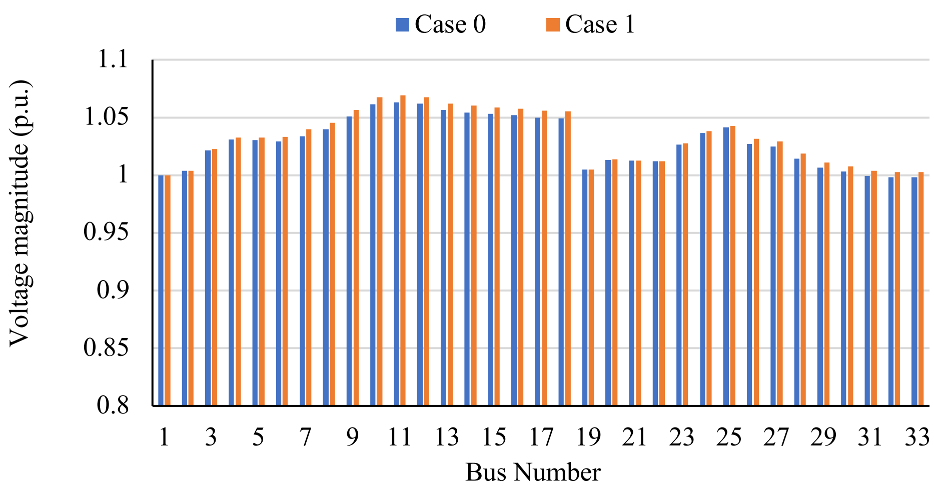

Figure 4.2: Comparison of voltage magnitude between Case 0 and Case 1, scenario 1.

4.3 Case 2: Optimal hosting capacity with network reconfiguration

In this case, the hosting capacity of the IEEE 33-bus is maximized by considering network reconfiguration. Table 4.4 details the results. In scenario 1, the optimal hosting capacity is determined to be 8542.0 kW. The power transfer to the main grid is also determined to be 4581.0 kW. In comparison with Case 0, the total hosting capacity has increased by about 90 kW, while power exchange from the main grid remains similar. This is perhaps due to the corresponding line limit. The optimal network reconfiguration solution yields all tie switches to be closed. Lines 14, 19, 21, 24 and 32 are further determined to be open. By comparing this case to Case 0, network reconfiguration has slightly increased the total hosting capacity without upgrading the grid.

Table 4.4: The Result for Case 2.

Scenario #	Scenario 1	Scenario 2
Total DG (kW)	8542.0	2960
Power exchange (kW)	-4581	802.4
Total loss (kW)	245.6	47.4
Voltage (p.u.)	0.91-1.004	0.95-1.00
Open lines	14,19, 21, 24, 32	20,21,24,34,36

In scenario 2, when DGs are only allowed to be installed at end buses, the hosting capacity of DGs has doubled the value of the corresponding scenario in Case 0, as shown in Table 4.5. A total capacity of 2960 kW is injected in end buses while the exchange power with the main grid is decreased to 802.4 kW. In comparison with Case 0, power losses have reduced by about 60%. In this scenario, closed tie switches are 33, 35 and 37 and lines 20, 21 and 24 are opened. Figure 4.3 presents comparatively the voltage profiles of scenario 1 in Case 0 and Case 2.

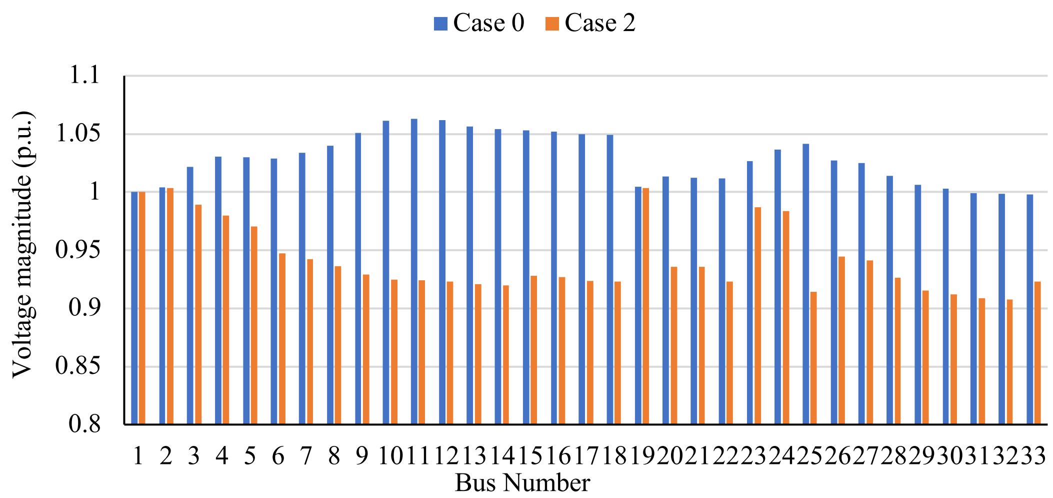

Figure 4.3: Comparison of voltage magnitude between Case 0 and Case 2.

4.4 Case 3: Optimal hosting capacity with ESS

ESS is considered to maximize the hosting capacity in this case. The ESSs are located at bus 12 and 20. In scenario 1, where DGs are allowed to be installed at all buses at the same time, the total hosting capacity is determined to be 10394.6 kW while the exchange power with the main grid remains close to Case 0. The newly determined hosting capacity is significantly larger than that of Case 0. In Scenario 2, the integration of ESSs have not made any improvement in DGs hosting capacity; however, the exchange power with the main grid has increased by about 700 kW.

Table 4.5: The result for Case 3.

Scenario #	Scenario 1	Scenario 2
Total DG (kW)	10394.6	1470
Power Exchange (kW)	-4580	3071.4
Total loss (kW)	100	139.5
Voltage (p.u.)	0.99-1.08	0.93-1.00
Total power charged (kW)	2000	686.8
ESS location	12 and 20	12 and 20

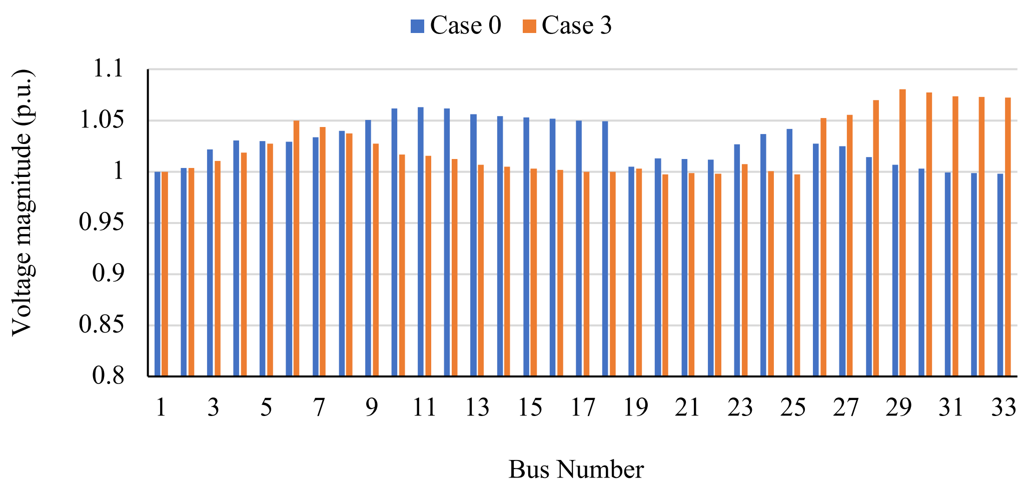

Figure 4.4: Comparison of voltage magnitude between Case 0 and Case 3.

4.5 Case 4: Optimal hosting capacity with network reconfiguration, ESS and, SVC

In this case, all previous methods are combined, Network reconfiguration, ESSs, and SVCs, to maximize hosting capacity. In the first scenario, as it is cleared from Table 4.6, the DG hosting capacity has increased by about 25.5% after combining all three approaches and apply them to the system. Moreover, in the second scenario, when DGs are placed at end buses, the hosting capacity of DG has increased by about 123% after combining all approaches and apply them to the system meanwhile the exchange power has decreased dramatically, and the ESSs have charged by 1000 kW. Furthermore, the voltage magnitude is maintained within acceptable limits. In short, the proposed model not only has significantly increased the DG hosting capacity but also it has reduced the power transferred from the grid.

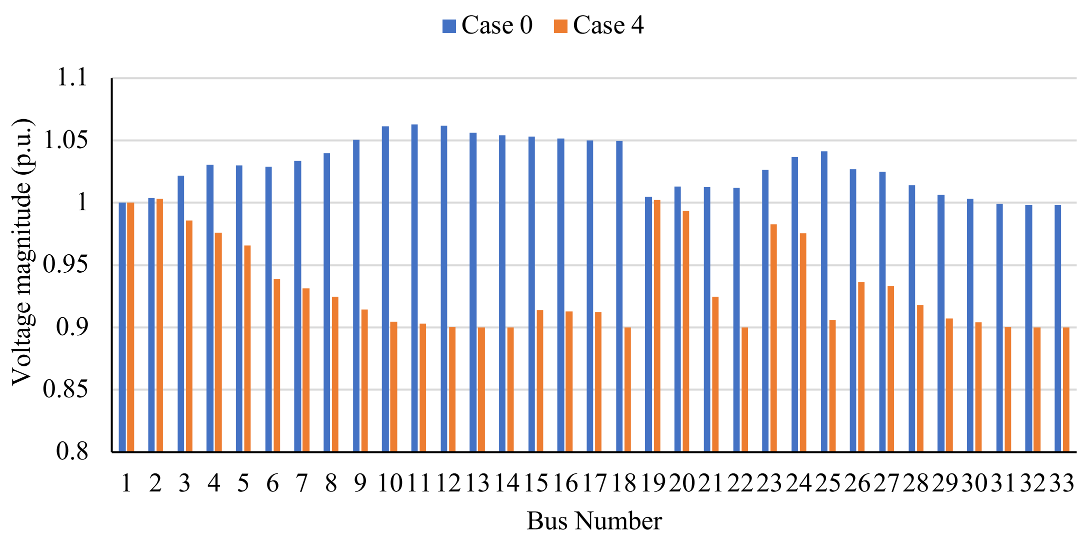

Figure 4.5: Comparison of voltage magnitude between Case 4 and Case 0.

Table 4.6: The result for Case 4.

Scenario #	Scenario 1	Scenario 2
Total DG (kW)	10607.7	3282
Power exchange (kW)	-4583	1540.7
Total loss (kW)	309.8	107.5
Voltage (p.u.)	0.90-1.0	0.93-1.00
Open lines	14,17,20,21,24	14,17,20,21,23
Total power charged (kW)	2000	1000
ESS location	12 and 20	12 and 20
SVC locations	7 and 24	7 and 24

4.6 Case 5: Sensitivity analysis of hosting capacity with respect to line limits

The sensitivity of the hosing capacity for Case 4 concerning line limits is discussed in this case. From the first scene in all cases, it is cleared that the line limit of the point of interconnection (POI) has limited the DGs hosting capacity in the distribution test system. Therefore, the limit of the line of the POI is changed to examine the effect of line limit to the hosting capacity. The line capacity is increased by 10% increments up to 50%. As shown in Table 4.7 and Figure 4.6, when the lines capacity limits are increased by 10%, 20%, 30%, 40%, and 50%, the hosting capacity has increased by 4.3%, 8.6%, 13%, 17.4%, and 21.7% respectively.

Table 4.7: The results for Case 5.

Line Capacity (%)	0%	10%	20%	30%	40%	50%
Line Capacity (kW)	4600	5060	5520	5980	6440	6900
Total DG Power (kW)	10607.6	11068.3	11528.8	11988.6	12450	12910.7
Power Exchange (kW)	4583	5039.1	5495	5950.5	6405.2	6860.5
Power losses (kW)	309	314	318.7	323	329.8	335.3

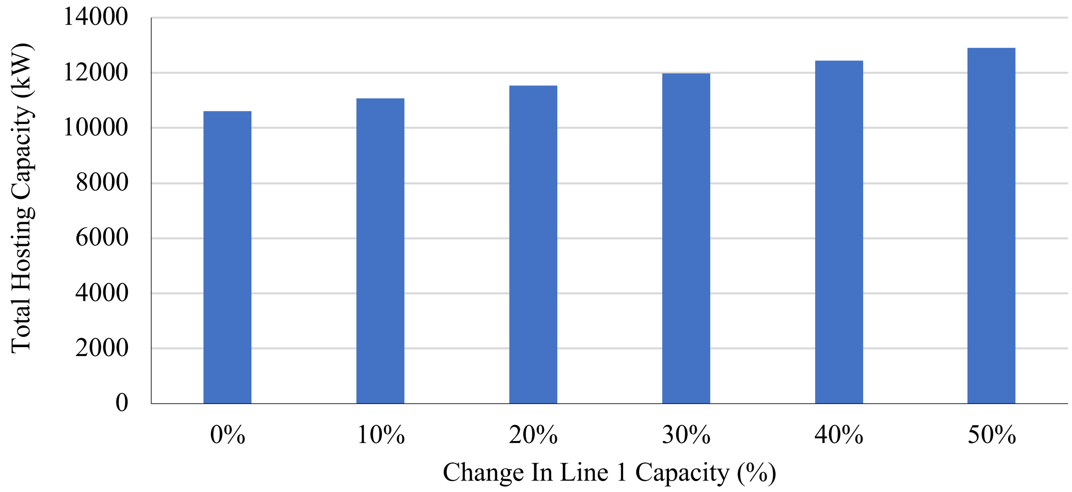

Figure 4.6: The change on the Hosting capacity with respect to capacity limits of lines 1.

Since the second scenarios have not reached the line limit of POI, they are not included in the study. Besides, the power loss is increased slightly by 1.6%, 3.1%, 4.5%, 6.7%, and 8.5% as the line capacity limit increased by 10%, 20%, 30%, 40%, and 50% respectively as shown in Figure 4.7. As shown in Table 4.7, the POI line capacity impacts the DGs hosting capacity where the hosting capacity increases as the line capacity increased. Therefore, upgrading a critical line limit in the system instead of the whole system has shown a significant improvement in the hosting capacity of the distribution system.

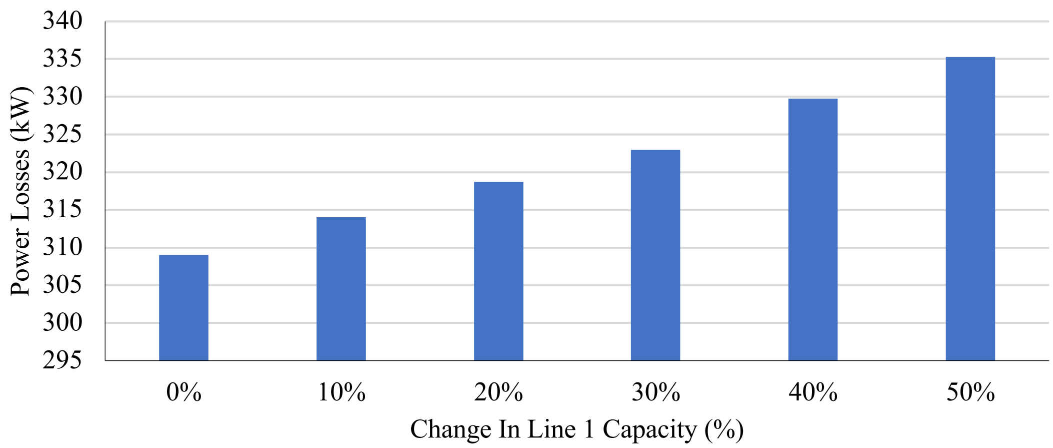

Figure 4.7: The change on Power losses with respect to capacity limits of lines 1.

Several methods to increase the hosting capacity of the distribution grid with different restrictions in DGs location are considered in this thesis. Figure 4.8 exhibits the changes in the hosting capacity along with the approach that is used. It is clear that DGs location and POI line capacity limits have a significant effect on the hosting capacity calculation. Moreover, the hosting capacity is increased along with ESS capacity while DGs are considered in all buses. However, the SVCs have slightly increased the hosting capacity and that due to the R/X ratio of lines. Finally, the proposed model applied on IEEE 33-bus system shows that the hosting capacity is maximized with maintaining the system's operational limits and avoiding any reinforcement in the grid.

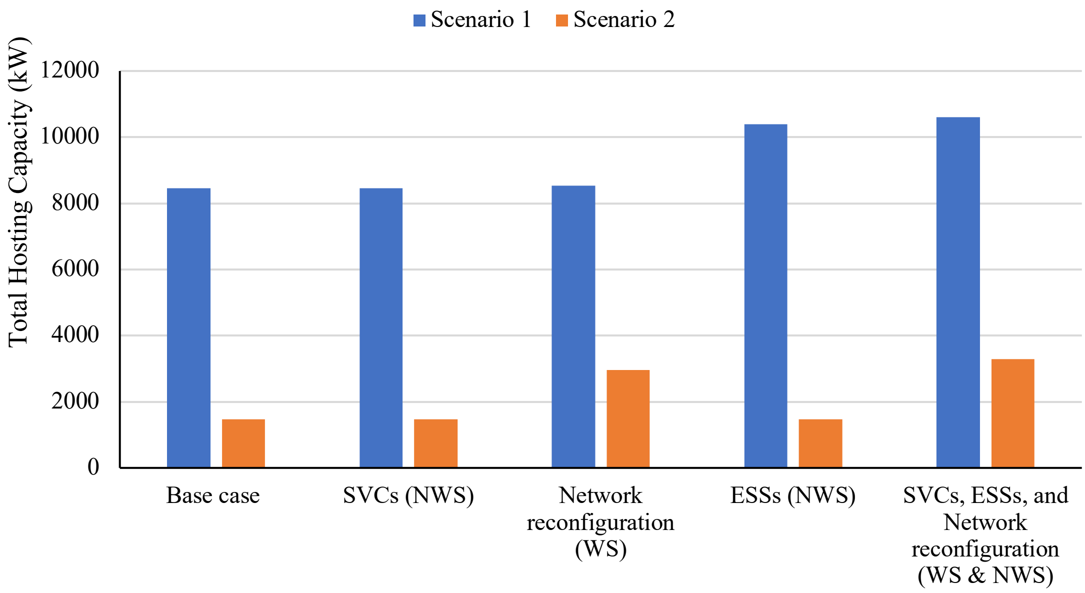

Figure 4.8: Comparison between all methods for both scenario.

Chapter Five: Conclusion

In this thesis, different methods that can significantly increases DG hosting capacity for the radial distribution network were proposed. The proposed model was analyzed through numerical simulations on the IEEE 33-bus system. A linearized AC power flow was employed. Three strategies were considered to increase hosting capacity, namely reactive power control using SVCs, network reconfiguration, and utilizing ESSs. The reconfiguration of the distribution grid has been programmatically encoded in the formulation while SVCs and energy storage systems have been added to the system at fixed locations. The ESSs significantly increased the DGs hosting capacity when DGs are allowed at all buses while network reconfiguration was more efficient for when DGs are considered only at end buses. The effect of SVC depends on the lines R/X ratio. By using the proposed wire and non-wire solution, the hosting capacity can be increased in the studied case as much as 25.5%.

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