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Reliability improvement of power systems using shunt reactive compensation and distributed generation

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ABSTRACT

Due to the increased demand on electric power, power systems have become highly stressed. This has caused the frequent occurrence of cascading failures, where the failure of one line leads to a series of failures causing a system blackout. Adding high speed control of different electrical parameters of the power system can help improve the reliability of the power system and relieve some of that stress. In this research, the effects of adding static VAR compensators (SVCs) and distributed generation units has been studied from a reliability perspective. Since installing this equipment can be expensive, an algorithm has been developed to obtain the optimal bus location to install such devices, such that reliability is improved. Furthermore, Monte Carlo simulation is used to provide a measure for the improvement in system reliability in the presence of transmission line failures. Results show that injecting real and reactive power generally improves system reliability. However, increasing the amount of injection and increasing the number of buses injected to indefinitely does not necessarily enhance the reliability of the system any further. As such, caution must be exercised when deploying SVCs or distributed generation sources when the goal is to improve system reliability.

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1. INTRODUCTION

In recent years, due to the increased dependence on electric power, transmission systems have increasingly become highly stressed, working very close to their capacity. This has led to the more frequent occurrences of cascading failures, in which the random failure of one or more transmission lines causes some of the remaining lines to become overloaded, triggering additional failures in the system, eventually leading to a system-level blackout. The flexible AC transmission system (FACTS) technology has made a lot of progress in the field of AC transmission systems. FACTS can provide high speed control of various electrical parameters such as voltage, current, phase angle, in addition to active and reactive power. This provides many opportunities for improving the operation of power systems, including control of power flow, boosting the loading capacity of the transmission system, and improving the overall system stability and reliability. FACTS devices can be installed individually or as a collection to control different parameters of the power system. They can overcome many limitations of power systems, including issues with thermal loading limits of transmission lines, undesired bus voltage fluctuations, or other undesired dynamic conditions.

A cascading failure occurs in a power system when the random failure of one transmission line, in a highly stressed system, causes an overload and subsequent outage in one or more additional transmission lines. This triggers additional overloads and outages in the system eventually leading to a system-level failure (blackout). A reliable power system is expected to supply customers with electrical energy in an economical and uninterrupted manner. Nowadays, such expectations are set to very high standards; and while this has proved to be challenging, the probability of a customer suffering from an interruption in electric power has been substantially reduced. One way this has been done is by studying the reliability and economic constraints during both the planning and operation phases of power systems. It has been shown that the reliability and economic constraints are generally acting in opposite directions, leading to difficult decisions in the operation of a power system. In recent years various techniques have been proposed in order to overcome these constraints [1]. These techniques have been deterministic in nature, which does not accurately reflect the stochastic nature of the power system behavior.

Probabilistic evaluation of system behavior has been recognized for over 60 years [2]. However, these methods have not been used due to the limitations of computational resources, including lack of data and real time reliability techniques, and due to the lack of understanding of the importance of the probabilistic criteria. However, these reasons are no longer valid as the computational abilities have increased immensely, and engineers have a better understanding of the significance of the probabilistic criteria with the development of reliability enhancement techniques.

Two types of evaluation techniques are mainly used to estimate system reliability; analytical methods and simulation. Analytical methods mainly use mathematical models to evaluate the reliability of components and systems; however, in a system as complex as a power grid, analytical solutions often lead to very complex models that are difficult to validate. As such, simulation methods, such as Monte Carlo simulation (MCS) can be used to accurately model the behavior of a power system, and provide a much better and easier estimate to the overall system reliability. The disadvantage of MCS is that it can take a lot of computation time to arrive at statistically reliable estimate of a power system reliability. The advantage is that it can easily be modified to include any desired effects that need to be taken into consideration when simulating the behavior of an electrical network, including the addition of distributed generation (DG) sources, or the effects of adding FACTS or other control devices to the grid [3] as we intend to do in this research.

In this paper, we investigate the effect of adding shunt reactive compensation at selected buses on the reliability of a power system. Static VAR compensators (SVCs), a type of FACTS device, are used to add reactive compensation at a number of buses in the system, and that effect is evaluated in terms of its effect on system reliability, and cascading failures in particular. The number of SVCs is set for each system according to its size, and their locations are varied to determine the optimal location for the SVCs to have an optimal effect on system reliability. In addition, DG sources are added to provide additional real power at the locations where VAR compensation is added.

Upon determining the best locations for the SVCs, additional simulations are performed using MCS to assess the actual improvement in system reliability due to the addition of SVCs and DG sources. A number of parameters are varied to evaluate the different aspects that can affect system reliability. Results show that adding SVCs and DG sources at carefully selected locations can significantly improve system reliability.

The rest of the paper is organized as follows: i) Section 2 provides a summary of the related literature; ii) Section 3 outlines the methodology used in this research; iii) while section 4 states the assumptions used and presents the simulation setup; v) Section 5 presents the initial results of the simulation; vi) In preparation for the MCS simulation which is presented thoroughly in section 6; and vii) Finally, section 7 concludes the paper and presents suggestions for future work.

2. LITERATURE REVIEW

In this section, we present a survey or related literature. A review of cascading failures is initially presented, followed by the effects of distributed generation on reliability, and subsequently, we survey the effects of FACTS technology on power system reliability. A summary of the methods for reliability evaluation in power systems is also presented.

Multiple studies have been conducted on cascading failures in power systems. For example, the work in [4] studies the nature of propagation of cascading failures. The initiated sequence of failures is determined by the stress of power on the system elements, while the period between the failures is determined by a stochastic processes. The model developed is checked against historical data, and the results showed a good degree of similarity.

Another proposed model is based on the node efficiency in complicated power systems [5]. The proposed model shows how a small failure such as removing one node can cause other failures and a blackout of the system. To measure the effect of the cascading failures, network efficiency has been used. Results show that the cascading failures are affected by tolerance of the overload and node capacity.

The reliability sensitivity analysis can determine weak parts of the power system, which has very important implications. The research done in [6] proposes a method where graphical representations of sensitivity and practical engineering requirements are analyzed. The proposed method can approximate and evaluate the sensitivity of widely used primary equipment in the power systems directly to meet the need for maintenance efficiently. A similar sensitivity analysis was also performed in [7] on the IEEE 30 bus system to assess the effect on reliability and potential cascading failures.

Despite the importance of studies on cascading failures, which are mostly transmission system failures, most of the work on power system reliability has been done on distribution systems, as presented in the following paragraphs. A number of standard reliability indices are used in the evaluation of reliability for distributed systems. The goal is mainly to evaluate the effects of distributed generation (DG) sources on power system (or just the distribution system) reliability. The main indices used in distribution system reliability are divided into two main types, load point indices and system level indices. Load point indices include i) expected energy not supplied (EENS) (in some papers simply ENS), ii) system average interruption frequency index (SAIFI), iii) system average interruption duration index (SAIDI), and iv) consumer average interruption duration index (CAIDI) which have been used in a number of papers including [8]-[14]. Power system level reliability indices include mainly: i) bulk power interruption index (BPII), ii) bulk power supply disturbance (BPSD), and iii) bulk power energy curtailment index (BPECI) which were mentioned in [15], [16].

The number of studies that use standard reliability indices are many. For example, the work in [8] studies the effect of DG sources in improving reliability of distribution systems. DG sources were added at selected locations at the end of distribution feeders. Reliability indices such as SAIFI, SAIDI, CAIDI, ENS were used to assess the reliability improvement. The work in [17] presents a review of reliability models for distribution systems with renewable energy distributed generation sources. Each type of renewable source is modeled analytically using Markov chain models that are specific to the nature of the source. The work in [18] also presents the use of DG sources to improve distribution system reliability. Similar studies include [10], [11], [13], [19] all of which evaluate the reliability of power systems after adding renewable energy sources, and using the above mentioned load point indices.

Additional studies such as [20] study reliability improvement in distribution systems due to DG sources. Results show that reliability improves with the addition of DG sources but only with relatively low values. Adding more DG sources will lead to reduced reliability. The study in [9] considers the optimal allocation of DG sources in distribution systems using genetic algorithms. The cost function was based on the overall benefit of adding DG sources versus the added cost of having DG sources. Constraints such as reliability improvement (SAIFI, SAIDI indices) and voltage profile and losses were also used as part of the optimization. Another study that focuses on the optimal placement of DG sources in [14], in which reliability indices such as SAIDI, SAIFI, and ENS are used. Similarly, the work in [12] considers optimal allocation of DG sources, but uses the customer average interruption duration index (CAISI) and the momentary average interruption frequency index (MAIFI) as the reliability indices. The work in [21] takes it a step further by combining a number of indices such as SAIFI, SAIDI, and EENS, and builds on them to define a more specialized index to assess the improvement in reliability due to the addition renewable sources. The work in [22] uses analytical methods to develop a reliability model for a smart grid that includes in addition to conventional sources, wind turbines, solar panels, and plug-in electric vehicles. The method is based on calculating the state space matrices for all components in the system and calculating the EENS of the system under various operating conditions.

While the use of DG sources to improve reliability has been proven generally successful, another technology; namely, the technology of flexible AC transmission systems (FACTS) devices has also been proven to improve the overall operation of the grid, including its stability, and reliability. As such, and since it is heavily used in this research, we will devote the next part of the literature to review some of the most relevant studies in improving the grid reliability using FACTS.

FACTS technology dates to the 1970s, and since the research done though Electric Power Research Institute (ERPI), they have improved drastically. One of the first devices, the static VAR compensator (SVC) was introduced in the late 1970s [23]. The SVC is a versatile device that provides voltage control, VAR compensation, and damping of oscillation, all of which can be used for various applications in power systems operation. Later, in 1986, the sub-synchronous resonance (SSR) damper was introduced. This damper had a thyristor control across a series capacitor. This resulted in the development of the thyristor controlled series capacitor (TCSC). The added thyristor controller to the series capacitor provided power control, series impedance control, damping of the oscillations, as well as transient stability. Details about the types of FACTS devices and their deployment levels are presented in [24].

SVCs have proven to be popular in a wide variety of applications. The general idea is that SVCs have the ability to keep the voltage profile at a specific bus within certain limits even under unusual fault situations. In addition, they can inject or absorb reactive power as needed within a specified range of operation to compensate for any changes in load requirements. SVCs, as such, can actually help maintain a reliable system operation, as they reduce the required amount of power transfers in the transmission lines; thereby adding a much needed extra capacity in the transmission system. This, in turn, can cause a more reliable system operation, as it reduces the possibility of cascading failures in the network.

A number of studies are presented below that explore the work on SVCs in terms of their effect on system operation, as well as their impact on reliability. The work in [25] presents a study in which both DG sources and distribution FACTS (DFACTS) devices are used to improve the voltage profile of the IEEE 33 bus system, and hence improve its reliability. The study in [26] uses genetic algorithms to determine the optimal allocation of FACTS devices to improve the voltage profile and reduce the losses in a power system, and hence, improving its reliability. The work in [16] shows how the unified power flow controller (UPFC); another type of FACTS device, can be used to improve the system reliability by evaluating its effect on the EENS load point reliability index as well as a number of system reliability indices. The work in [15] presents a similar work but uses the thyristor-controlled series capacitor (TSCS) as the FACTS device of choice to also improve system reliability.

The work in [27] evaluates the effect of the SVC and the thyristor controlled phase angle regulator (TCPAR) on the power system reliability by evaluating the EENS using MCS. On the other hand, the study in [28] qualitatively analyzes the operation of an SVC and its ability to provide voltage support in normal operating conditions as well as contingency situations. It also provides a detailed analysis and real life experience events related to failures in the operation of SVCs, outlining the main factors contributing to such failures, and hence affecting its reliability.

Additional papers describing the effects of SVCs include [29], [30]. Hamzah and Yasin [29] describe the use of SVCs in improving voltage profile during faults, and presents a number of case studies in that regard, while Bostrom *et al.* [30] provides a case study of reliability improvement in a power system using SVC. The SVC was used to provide fast acting voltage support in the event of line contingency to prevent voltage collapse. The work of [2] has also shown the effect of installing SVCs with electric arc furnaces in power plants and distribution systems. Electric arc furnaces cause harmonics and affect the power factor. To compensate for that, SVCs can be installed to absorb or inject reactive power thus improving the power factor and removing harmonics.

The combinations of other technologies with FACTS technology have also been proven to have a positive impact on the system operation as well. In [31], system component failures are represented using fuzzy numbers for the analysis of the reliability of the system as well as the analysis of the generation and transmission systems. Using fuzzy logic, many parameters of the system can be obtained to include data uncertainty in normal calculations. The TCSC model in addition to the fuzzy model are used to study the effect on the system.

In [32] the incorporation of FACTS technology in a composite electric power system shows that in certain cases, they have some positive impact on the power system reliability. Two reliability testing systems have been used to conduct multiple studies; the Roy Billinton test system (FU3TS) and the IEEE reliability test system (IEEE-RTS). The impact of FACTS devices is shown to be highly dependent on two factors; loading condition of the transmission system, and the locations where the FACTS devices are installed.

Mahdad [33] proposed a method of combining a renewable sources; namely wind generators, and dynamic shunt FACTS devices to improve the control and the quality of the power system. The proposed algorithm and concept have been tested on the modified IEEE 30 bus system. The result of the study showed that the proposed system can improve the power quality by reducing power losses and voltage deviation. The reduction of those parameters especially the voltage deviation can improve the overall reliability of the power system.

The work in [34] shows that control of power flow can be achieved by installing FACTS devices at the distribution level. These devices are similar to the original FACTS devices but with reduced power rating. In general, distributed FACTS provide better performance and cost less. For example, a distributed static series compensator (DSSC) can replace the static synchronous series compensator (SSSC), which provides capacitive and inductive compensation. The study showed the DSSC FACTS devices increase the reliability of the power system.

The work of [35] showed that the addition of the UPFC enhances the system's performance in normal and transient conditions. It also reduces fault current magnitude and excitation voltage oscillations. The work in [36] shows how the cyber control on UPFCs, including software related failures, can also contribute to the reliability of the system.

The work in [37] has introduced a method to improve the reliability of a system using FACTS devices and HVDC equipment application. The combination of the two technologies can be a method to optimize power flow, increase reliability, and the provision of the stability of the system voltage. The impact of installing SVCs at different locations in the IEEE 14 bus system has been studied in [38]. This study shows the effect of the fast-acting reactive power injection on high voltage electrical systems. The results of the simulation were provided by running the Neplan software, which shows that to improve the voltage level of the IEEE 14 bus system, SVCs are to be installed in buses number 4 and 5.

In terms of reliability evaluation techniques, probabilistic methods and Monte Carlo simulation (MCS) were extensively used. Simulation can be used to assess the reliability of various types of power systems. The research done by [3] shows that the assessment of reliability for limited energy systems is possible. However, it requires extra detailed models for multiple factors such as external and internal generating dispatch, the availability of primary generating resources, in addition to customer demand. The method proposed shows a sequential MCS technique with AC power flow for long term reliability assessment. It is also shown that assessing the reliability of energy-limited systems is more accurate due to the high correlation between the reality and the models, thus decreasing the risk in decision making.

The work of [39] shows another method of adding a renewable sources to the power system to enhance the reliability. This method consists of adding photovoltaic (PV) sources to the power system. MCS is used for the reliability assessment of the system. The results show that the addition of the PV sources enhances system reliability to an extent; however, any further increase in the PV sources may have negative effects. This is also confirmed in [40] where the author shows a decrease in reliability after the PV penetration level was increased beyond a specific value.

This study utilizes the SVC's ability to inject reactive power (VAR compensation) to specific load buses in the power system. We assess the effect of adding SVCs in strategic locations on the overall system reliability, and develop a mechanism to find the optimal location for placing the SVCs to maximize their impact. In addition, we consider the effect of injecting real power as well at the same bus locations in the form of renewable generation sources. Furthermore, Monte Carlo simulation is used to validate the results obtained, and provide an accurate representation of the reliability improvement in the system.

3. RESEARCH METHODOLOGY

To implement our algorithm, and to perform the necessary simulations, we used the MATPOWER package [41], which is a MATLAB-based library of functions that can be used to simulate power flow in a given power grid. Our methodology is performed on three IEEE standard test systems; namely, the IEEE 14 bus system, the IEEE 18 bus system, and the IEEE 30 bus system. Three different systems were used to implement our algorithm, in order to show its validity under different system dynamics, and system sizes.

3.1. Setting line capacity

MATPOWER can be used to run several types of power flow algorithms on a given system. This includes the regular AC power flow, DC power flow, and optimal power flow among others. In our work we use the regular AC power flow to determine the operating power flow values for the system. The transmission line capacities of each system are determined as a function of the rated power flow values of the lines. To set the line capacities, we simulate the operation of a normally functioning system, and determine the amount of power flowing in each transmission line in the system. This is designated as the rated power of the line. Line capacity is then determined as a value that is a certain percentage above this base value. For the purposes of this study, the line capacity used were 150% of the rated values.

3.2. Simulating cascading failures

Cascading failures are an important part of this study. To simulate a cascading failure we need to define its meaning clearly. Given the line capacities set in the system as described in 3.1, we can run the power flow algorithm, while introducing random failures at specific lines in the network. After the failure of one or more transmission lines, we check if the power flow in any of the remaining lines violates the set line capacity. If and when that occurs, the violating line (or lines) are removed from the system to simulate their outage, and then the power flow algorithm is run again, until the system either converges without any further overloads, or a blackout occurs. More specifically, the following steps are run to simulate a cascading failure:

- An initial transmission line fault is simulated by setting the transmission line impedance to infinity, indicating that there is an outage in that line, and it was removed from the network.
- Power flow is run using MATPOWER, and the power flow in each remaining transmission line is calculated.
- Lines are checked against the capacity of the lines to determine if any of them is overloaded.
- If power flow converges, and no lines are overloaded, we say that the system remains functional, despite the failure of one transmission line. No cascading failure occurs, and the system continues operation.
- If one or more lines are overloaded, those lines are removed from the system to simulate their outage, and power flow is run again.
- The process is repeated until either there are no more overloads and the system continues operation despite the failure of one or more lines, or the lines continue to get overloaded, and fail until a blackout occurs, as indicated by the fact that power flow can no longer converge.

3.3. Addition of reactive compensation

Reactive power compensation is performed in real-life using capacitor banks, or using a FACTS device, such as the SVC or the STATCOM. This effect is simulated in MATPOWER by adding a source that provides only reactive power to the desired buses in the system. This is implemented by converting a load bus into a generator bus, and setting the generated reactive power to its desired value.

3.4. Addition of distributed generation sources

Similar to the addition of reactive compensation, real power can be added to the system at any desired bus locations, to simulate the effect of a distributed generation source, such as a solar farm or a wind farm. The desired bus is converted into a generation bus, and the real power generated is set to the desired value. In the next section, we use the operations mentioned in this section, to develop our algorithm for optimal placement of SVCs.

4. DETERMINING OPTIMAL BUS LOCATIONS

SVCs, and FACTS devices in general, are expensive devices, and while it is useful to add as many devices to the system as we can, its high cost makes it prohibitively expensive to do so. Therefore, it is best that a few such devices are placed in certain locations in the system such that we maximize their benefit. In this section, we develop a mechanism for deciding the number and location of SVCs for the IEEE test systems used in this study. The aim is to use only a few SVCs on each system, and find the optimal locations to place them so that their effect on system reliability is maximized. The following steps were used in determining the optimal location for installing SVCs in the system:

a. The following initialization parameters are entered:

- Detailed IEEE test system information.
- Percentage or number of buses at which SVCs are to be installed. The number is set to a value n.
- The line capacity of every line in the system.
- Amount of required reactive power (VAR) compensation to be provided by each SVC.

b. Prepare a list of all possible n-bus combinations in the system. These combinations will be tested to determine the optimal combination for installing SVCs. Note that if the total number of buses in the system is N, the the total number of combinations is:

$$\binom{N}{n} = \frac{N!}{n!(N-n)!} \tag{1}$$

c. Run an initial fault-free power flow to determine the rated flow values in the transmission lines. Calculate the apparent power as:

$$S = \sqrt{P^2 + Q^2} \tag{2}$$

where P and Q refer to the real and reactive power flows, respectively, for each transmission line under normal normal operating conditions. Set the line capacities as a percentage of the rating (e.g. 150%).

d. After listing all possible n-bus combinations in the system, perform the following steps:

– For each n-bus combination, connect an SVC to each bus, and set the amount or reactive compensation desired.
– Introduce a transmission line failure in one branch in the network and run power flow. If this failure causes additional overloads/failures in the network, remove the additional failed lines, and repeat until either the system converges or a blackout occurs.
– Record the total number of overloaded lines, and the total amount of overload in all lines before the blackout occurred.
– Repeat this process for all remaining transmission lines in the system.

e. After completing the previous step, a set of results are obtained determining the total number of line overloads, and the total overload for each possible combination of n-buses. The n-bus combination that resulted in the least number of line overloads and the least amount of overload is chosen as the optimal candidate for adding SVCs. This n-bus combination will be further validated at a later stage using Monte Carlo simulation (MCS), which will be described in section 6.

f. (Optional) after determining the optimal bus location for SVC installation, augment the buses by adding a specified amount of distributed real-power generation at the same buses.

5. INITIAL RESULTS AND DISCUSSION

In this section, we present the simulation parameters used for the three IEEE test systems used in this simulation. We also present the results of determining the optimal bus locations, given the set parameters.

5.1. Assumptions and test values

The following simulation cases will be simulated for each system:

– Capacity will be set to 150% of the rated power flow on each transmission line.
– The number of buses on which SVCs are installed will be varied as follows:
For the 14 bus system: 2, 3, and 4 buses.
For the 18 bus system: 3, 4, and 5 buses.
For the 30 bus system: 4, 5, and 6 buses.
– The amount of VAR compensation will be set at one of three values, as a percentage of the load: 30%, 40%, and 50%.
– The amount of real power distributed generation (DG) to be added will be 20% of the total centralized power generated, and will be distributed equally among the designated buses.

5.2. Results

This section demonstrates the simulation results after applying the algorithm proposed in section 4 to three standard IEEE bus systems mentioned earlier. Table 1 presents the results of running the simulation without any added reactive compensation. These will be used as a control case to compare the effect of adding SVCs to the baseline case of no reactive compensation. We present the results of running our algorithm for optimal placement of SVCs on the three test systems. The results are presented for two cases of real power injection; namely, with or without real power injection; hereby designated as DG in the tables.

Table 1. Summary of results without reactive power compensation

	No reactive power compensation		
IEEE bus system	Line capacity (as a percentage of rating)	Total number of line overloads	Total sum of overloads (in MVA)
14	150%	67	1601
18	150%	75	869380
30	150%	152	37958

5.2.1. Results for the IEEE 14 bus system

Tables 2 through 4 show the optimal placement results for SVCs in the IEEE 14 bus system, for different levels of VAR compensation, at the line capacity of 150% as explained in the assumptions in section 5.1. Taking a look at the tables, we observe some improvements in the operation of the various test systems. It is observed that the sum of overloads has decreased approximately by 30 MVA, while the total number of overloaded lines has decreased from 67 to approximately 60 lines. It is obvious that the addition of SVCs had a positive contribution to the number of overloads and the overall sum of overloads in the system. Moreover, the addition of more SVCs did not seem to give a significant improvement in the results. Nonetheless, having more SVCs was an improvement, despite it being a small one, and did not have a negative effect on the operation of the system. It remains to be decided, whether the additional SVCs are worth adding to the system, given their extremely high price. More interestingly, when both real and reactive power are injected in IEEE 14 bus system, we can observe a much more significant improvement in the operation of the system, as the sum of overloads has decreased from 1601 MVA to approximately 500 MVA, while the number of overloaded lines has decreased from 42 lines to 28 lines in the highest case, and a mere 11 in the lowest.

Table 2. Case: IEEE 14 bus system, capacity 150%, VAR compensation: 50%

Number of buses per combination	Optimal bus locations for VAR compensation		Number of overloads		Minimum sum of overloads (in MVA)	
	No DG	With DG	No DG	With DG	No DG	With DG
2	9, 10	4, 14	61	28	1573.50	536.97
3	10, 13, 14	7, 10, 14	59	18	1571.00	506.09
4	5, 10, 13, 14	9, 10, 13, 14	59	11	1570.70	504.86

Table 3. Case: IEEE 14 bus system, capacity 150%, VAR compensation: 40%

Number of buses per combination	Optimal bus locations for VAR compensation		Number of overloads		Minimum sum of overloads (in MVA)	
	No DG	With DG	No DG	With DG	No DG	With DG
2	9,13	4, 14	62	29	1571.40	552.44
3	9,10,13	7, 10, 14	60	18	1571.90	506.73
4	4, 10, 11,13	9, 10, 13, 14	60	11	1571.20	505.08

Table 4. Case: IEEE 14 bus system, capacity 150%, VAR compensation: 30%

Number of buses per combination	Optimal bus locations for VAR compensation		Number of overloads		Minimum sum of overloads (in MVA)	
	No DG	With DG	No DG	With DG	No DG	With DG
2	9, 10	4, 14	61	29	1572.70	552.78
3	9, 10, 13	7, 10, 14	60	18	1571.80	507.40
4	5, 9, 10, 13	9, 10, 13, 14	60	11	1571.60	505.37

5.2.2. Results for the IEEE 18 bus system

Tables 5 through 7 present the results obtained for running the optimization algorithm on the IEEE 18 bus system. The results are generally quite similar to the results of the IEEE 14 bus system. The reactive power injection has resulted in decreasing the total number of lines that overloaded 75 to a value in the range between 14-30 lines. The total sum of overloads has also decreased from a high of 869380 MVA to values in the range of 100000 MVA, and sometimes to much lower values, with the exception of two cases when the sum of overloads actually rose to approximately 11,000,000 MVA. These two cases, however, behaved much better, when real power was also added. When injecting both real and reactive power to the IEEE 18 bus system, we observe a slightly better improvement by decreasing the number of overloaded lines and the total sum of overloads. A lowest total sum of overloads is observed at about 42,000 MVA, with a total number of overloads as low as 17.

Table 5. Case: IEEE 18 bus system, capacity 150%, VAR compensation: 50%

Number of buses per combination	Optimal bus locations for VAR compensation		Number of overloads		Minimum sum of overloads (in MVA)	
	No DG	With DG	No DG	With DG	No DG	With DG
3	4, 7, 17	7, 9, 12	29	30	94593	94467
4	4, 7, 8, 11	3, 4, 8, 15	26	30	96987	98890
5	6, 10, 13, 14, 16	3, 6, 9, 11, 13	19	21	69304	77395

Table 6. Case: IEEE 18 bus system, capacity 150%, VAR compensation: 40%

Number of buses per combination	Optimal bus locations for VAR compensation		Number of overloads		Minimum sum of overloads (in MVA)	
	No DG	With DG	No DG	With DG	No DG	With DG
3	5, 6, 9	2, 12, 17	28	27	11305000	94488
4	4, 6, 13, 18	5, 10, 15, 16	19	17	93675	42724
5	5, 9, 12, 14, 18	5, 8, 10, 16, 18	19	20	93892	43379

Table 7. Case: IEEE 18 bus system, capacity 150%, VAR compensation: 30%

Number of buses per combination	Optimal bus locations for VAR compensation		Number of overloads		Minimum sum of overloads (in MVA)	
	No DG	With DG	No DG	With DG	No DG	With DG
3	2, 4, 12	2, 12, 17	28	27	96301	94488
4	5, 6, 15, 18	5, 10, 15, 16	27	17	93635	42724
5	2, 5, 6, 15, 18	5, 8, 10, 16, 18	27	20	93635	43379

5.2.3. Results for the IEEE 30 bus system

Tables 8 through 10 present the results obtained when running the optimization algorithm on the IEEE 30 bus system. As in the previous two systems, an improvement in the system operation can be observed comparing the results of the simulation. The total number of overloaded lines was reduced from 152 to values in the range of 86-112. The total sum of overloads is also reduced from values in the range of 30,000 MVA to values in the range of 10,000 MVA when only adding reactive compensation.

Things were, however, different when adding real power as well. The observed results, show an increase in the total sum of overloads when adding real power in addition to the reactive power compensation. This is odd, compared to the IEEE 14 and IEEE 18 bus systems, but it signals an important difference between the systems, and shows that adding real power beyond a certain value, may not necessarily be a good thing, even if reactive power compensation provided an improvement in the overall operation. An explanation to this situation might be related to the nature of the load in the said system, as reactive power might be more needed than real power to cover the needs of the loads in the system. As such, while the general result in this work can be stated in a way that shows the benefit in adding reactive compensation to particular buses, the results may not necessarily be extended to also cover for real power as well.

Another reason for these results can be obtained from considering the fact that optimization was done with only reactive power considered. Real power was simply added to the buses that were considered the optimal locations for adding reactive compensation. To allow for both real and reactive power to be added at optimal location, a different set of optimization parameters should be used to obtain the best results. As the focus of this paper is to mainly consider the effect of reactive compensation, the results obtained will suffice. An optimal solution that considers both the effects of real and reactive compensation will be left for future work.

As a general conclusion for this section, we can conclude that increasing the line capacities and injecting reactive power to the optimal bus locations improves the operation of a system in terms of its reliability. Subsequently, injecting both and real reactive power may of may not further improve the reliability of the system based on the nature of the loads. Another result that is shown is that increasing the percentage of reactive power injection and increasing the number of buses does not necessarily mean that the parameter values will continue to improve. As such, a more rigorous optimization should be performed taking into account not only the bus locations, but also the level of reactive compensation and real power compensation that will achieve the optimal results. In the following section, we further validate the results obtained by running a monte carlo simulation for the same test cases presented in this section, to provide an even more accurate measure of reliability.

Table 8. Case: IEEE 30 bus system, capacity 150%, VAR compensation: 50%

Number of buses per combination	Optimal bus locations for VAR compensation		Number of overloads		Minimum sum of overloads (in MVA)	
	No DG	With DG	No DG	With DG	No DG	With DG
4	7, 12, 19, 24	3, 4, 5, 7	86	100	9693	58474
5	3, 7, 12, 18, 24	3, 4, 6, 7, 8	86	102	9693	36999
6	3, 5, 6, 7, 9, 17	3, 5, 6, 7, 9, 17	100	100	9611	9611

Table 9. Case: IEEE 30 bus system, capacity 150%, VAR compensation: 40%

Number of buses per combination	Optimal bus locations for VAR compensation		Number of overloads		Minimum sum of overloads (in MVA)	
	No DG	With DG	No DG	With DG	No DG	With DG
4	7, 8, 12, 24	3, 4, 7, 8	103	93	9711	47558
5	7, 8, 15, 18, 26	3, 4, 6, 7, 8	92	100	7068	13582
6	3, 7, 8, 10, 18, 24	3, 4, 5, 7, 8, 10	88	90	9065	9676

Table 10. Case: IEEE 30 bus system, capacity 150%, VAR compensation: 30%

Number of buses per combination	Optimal bus locations for VAR compensation		Number of overloads		Minimum sum of overloads (in MVA)	
	No DG	With DG	No DG	With DG	No DG	With DG
4	7, 12, 19, 24	3, 4, 6, 7	112	102	9886	591340
5	3, 7, 12, 18, 24	3, 4, 6, 7, 8	100	102	9802	471980
6	3, 7, 12, 18, 19, 24	3, 4, 5, 7, 8, 10	88	103	9751	35569

6. MONTE CARLO SIMULATION

6.1. Introduction

To further validate the results obtained in section 5, we perform Monte Carlo simulation (MCS) on the three test systems used in this study, and measure the improvement in system reliability due to the action of SVCs and DG sources. To measure the effectiveness of the real and reactive power injection, we run MCS in such a way that randomly introduces transmission line failures in the system, and simulates the effect of this failure on the overall operation of the system. Subsequently, we measure the time needed for the entire system to fail. The longer it takes for the system to fail, the more reliable it is. The result of this simulation is captured by the parameter "mean time to blackout" or MTTB, which will be explained in the following subsections.

6.2. Simulation setup

An initial line failure is assumed to be purely random. All lines in the bus system are assumed to have the same probability of failure with an exponential failure rate. The probability density function (pdf) is assumed to be:

$$f(t, \lambda) = \lambda * e^{-\lambda * t} \tag{3}$$

where λ is defined as the failure rate for the transmission line and can be found by taking the inverse of the mean time to failure (MTTF) for the line. The MTTF for each transmission line in this simulation is assumed to be 1 year. The choice of the value is arbitrary, as the results can simply be scaled appropriately for a different value.

Monte Carlo simulation will be used in combination with load flow to simulate the operation of each system. Initially, all lines are set to be operational. As time advances, it is inevitable that one of the lines will fail according to the exponential failure rate function in (3). Similar to the algorithm proposed in section 3, after removing the initial line that failed, power flow analysis is run again and the power flow in each line is calculated. If a line is overloaded, i.e., the power running through the line has exceeded the allowed capacity, the line is disconnected due to the action of protective equipment and is subsequently removed from the system. If, after the removal of the line, the system converges, we assume that the system remains operational, and advance the time step. If the simulation does not converge, we conclude that a blackout has occurred. Since the MTTF is assumed to be one year the time advances in steps of 1 day. The number of days the takes the system to blackout will be defined as "time to blackout" (TTB). The simulation has been repeated 100 times to obtain a statistically valid result. By taking the mean value of all the TTB values obtained, we can obtain the MTTB, which will be used to assess the overall system reliability. MTTB is an indication of the reliability of the system; the higher the value of the MTTB the more reliable the system is.

6.3. Simulation results

This section shows the simulation results of the MCS. The line capacity and the level of real and reactive power injection are set to the same values used in section 5. For the graphs shown in the following subsections, (I) stands for percentage of reactive power injection, and (C) stands for the line capacity set. The number of busses at which SVCs are connected is also shown.

6.4. The IEEE 14 bus system simulation results

Figures 1 and 2 show the results of the MCS for the IEEE 14 bus system, for the two cases described earlier; namely, case 1 being the injection of only reactive power, and case 2 is the injection of both real and reactive power. Considering the results, we can observe general improvements in the reliability of the power systems, compared to the base case, although not all tested cases provide an equal improvement. By merely increasing the line capacity, MTTB is improved, and in many cases, injecting real and reactive power has increased the value of the MTTB thus improving the reliability of the system. It can also be observed that injecting both real and reactive power to the system improves the MTTB slightly more than injecting reactive power only, as can be observed by comparing the respective entries of Figures 1 and 2.

It is noted that the MTTB has improved from 108 days in the base case to on an average of 118 days due to reactive power injection, but it improves to an average of 120 days when both real and reactive power are injected. The best results are shown when reactive power injection is set to 50%. The best MTTB value obtained is 128 days when setting the line capacity to 150% of the original line rating and injecting both real and reactive power into two buses; namely 4 and 14 with the level of reactive power injection set to 50%.

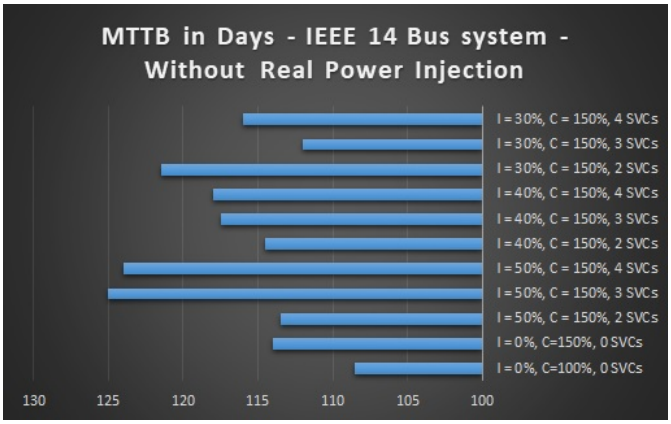

Figure 1. Monte Carlo simulation - IEEE 14 bus system - no real power

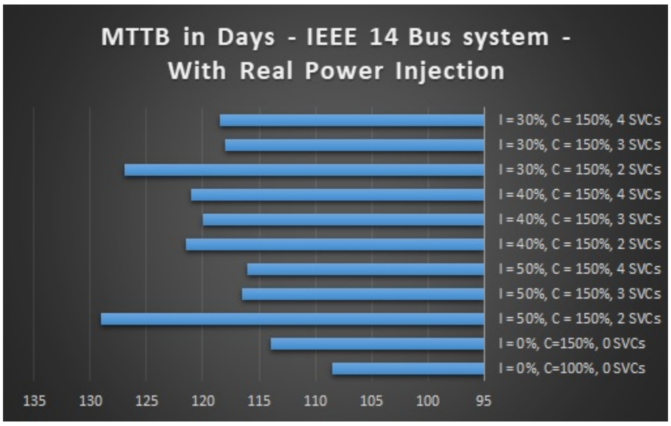

Figure 2. Monte Carlo simulation - IEEE 14 bus system - with real power

6.5. The IEEE 18 bus system simulation results

Figures 3 and 4 show the results of the Monte Carlo simulation for the IEEE 18 bus system, for the two cases described earlier; case 1 being the injection of only reactive power, and case 2 is the injection of both real and reactive power. Results show improvements in the reliability of the power system but not as much as the IEEE 14 bus system. Note that the system's MTTB has improved from 18 days in the base case to an average of 21.4 days when both real and reactive power are injected as shown in Figures 3 and 4, respectively.

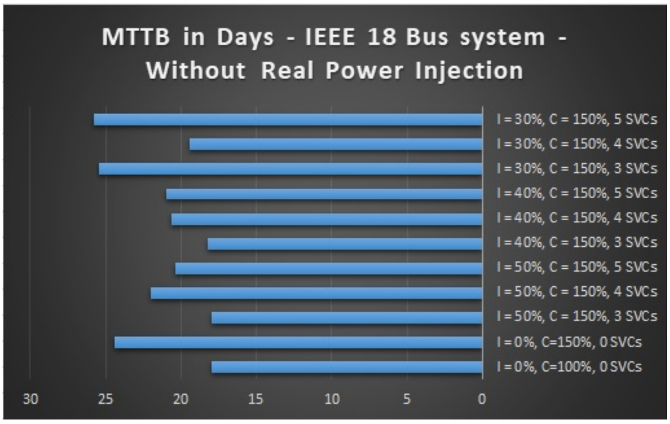

Figure 3. Monte Carlo simulation - IEEE 18 bus system - no real power

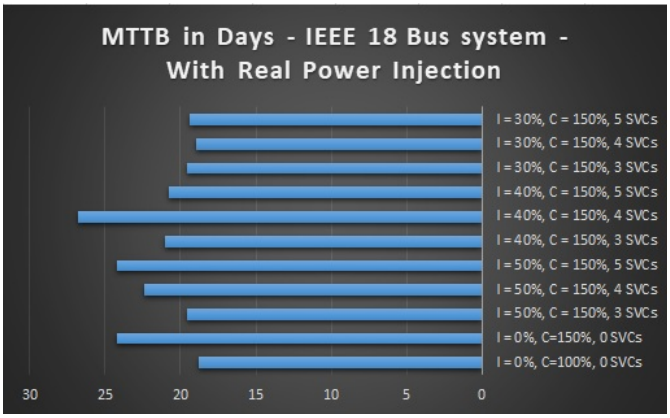

Figure 4. Monte Carlo simulation - IEEE 18 bus system - with real power

The results are similar to the IEEE 14 bus case, but the improvement is less. The increase in the injection amount as well as the number of buses does not necessarily mean there is an improvement in the MTTB value. The best MTTB value obtained is 30 days when setting the line capacity to 150% and injecting both real and reactive power into four buses; namely, 5, 10, 15, and 16, with the reactive power injection level set at 40%. The smallest value of the MTTB obtained is 19 days, which is also observed in multiple cases. When only injecting reactive power, however, it is observed that the highest values obtained are when setting the line capacity to 150% and the reactive power injection level is set to 30% on using 5 SVCs.

6.6. The IEEE 30 bus system simulation results

Figures 5 and 6 show the results of the MCS for the IEEE 30 bus system, for the two cases described earlier; case 1 being the injection of only reactive power, and case 2 is the injection of both real and reactive power. We can see an improvement in the MTTB value from 56 days to about 58.3 days on average when no real power is injected, and to about 59 on average, when also injecting real power. However, there are cases where the MTTB is the same for the original case even after injection. The best MTTB value obtained is 62 days when setting the line capacity to 150% of the original line rating and injecting real and reactive power into five buses (3, 4, 6, 7, and 8) with the injection level set at 30%. A very close value of 61.8 days was also observed when injecting both real and reactive power as shown in Figure 5. Further analyzing the results of the IEEE 30 bus system, of section 5.2.3, we can see a consistency in terms of the results of injecting both real and reactive power. Note that results are generally worse than injecting reactive power only, as observed by the generally lower values of MTTB for the case of injecting both real and reactive power.

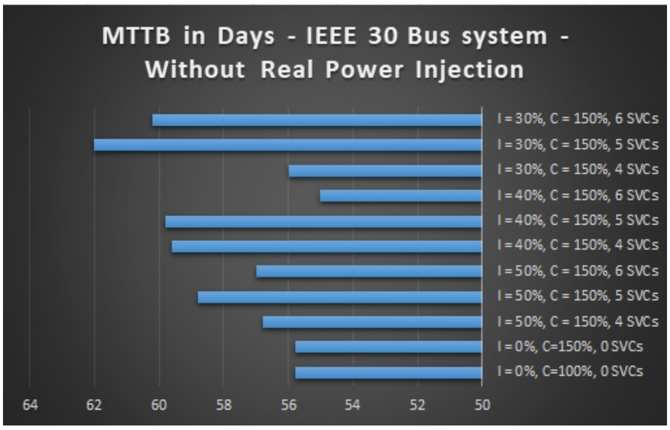

Figure 5. Monte Carlo simulation - IEEE 30 bus system - no real power

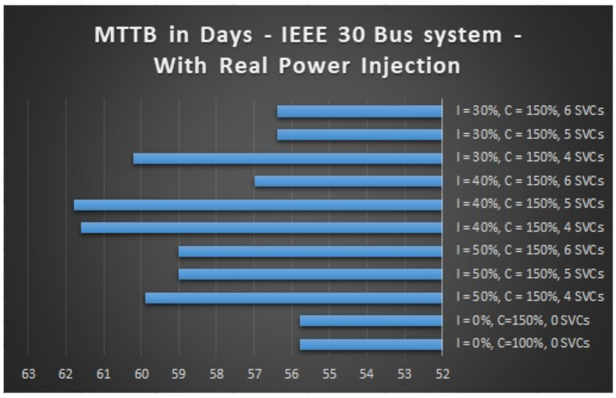

Figure 6. Monte Carlo simulation - IEEE 30 bus system - with real power

6.7. General remarks

Considering all the results obtained in this work, we can arrive at the following general conclusions:

- A general improvement in reliability is observed when injecting reactive power, or both real and reactive power to the system.
- Increasing the line capacity and increasing the amount of reactive power injection indefinitely does not necessarily improve the value of the MTTB any further.
- Similarly, increasing the number of buses on which to inject real and reactive power does not necessarily improve MTTB.
- Optimizing the location of SVCs can lead to better results in terms of overall improvement of MTTB, and hence system reliability; however, the addition of real power DG sources, should be optimized separately to obtain the maximum benefit.
- The larger the bus system, the lower the improvement on the MTTB value.

7. CONCLUSION

The electric power grid is increasingly becoming more and more overloaded due to the continuous increase in demand. This has caused cascading failures to occur more frequently, typically leading to blackouts. Static VAR compensators (SVCs), are a type of FACTS device that can be used to provide a much needed improvement for system reliability, by providing reactive power compensation at strategic locations in the system. In this paper, we incorporate SVCs to inject reactive power at specific locations in the grid, to enhance the reliability of the power system. An algorithm was developed to locate the optimal locations for installing SVCs to yield the best results from a reliability perspective. In addition, distributed generation has been used to also inject real power into the bus system. To further validate the correctness of the algorithm, a Monte Carlo simulation was performed for each system to measure the reliability improvement, through the measurement of the mean time is takes for a blackout to occur. Results show that while there is a general improvement in reliability when using SVCs and DG sources, it is important that the location of the SVCs be chosen properly as not all locations are equally useful in terms of improving reliability. Suggestions for future work include studying the potential of series compensation in reducing the risk of cascading failures, studying the effects of renewable sources, including their highly intermittent nature on system reliability, in addition to developing an optimization scheme that takes into consideration the multiple factors contributing to system reliability, and finding the optimal balance that achieves the desired results through a mix of distributed generation sources, and appropriate FACTS devices.

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