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Stochastic assessment of voltage sags and techno-economic optimization

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ABSTRACT

Power quality has become an essential concern for industries and domestic energy consumption with the development of sophisticated equipment like micro-electronic devices. When a power quality event happens, such as voltage sag, financial losses for industries increase tremendously. Therefore, voltage sag evaluation becomes crucial for predicting the number of events and severity of voltage sag events of the electrical network. Industries can determine the mitigation investment needed for optimal operation using the knowledge obtained through voltage sag analysis method. Thus, the first part of the study addressed the development of a stochastic assessment method for voltage sag at an interested bus in the power system network, which was an initial objective of the study. The second part of the research investigates dynamic voltage restorer (DVR) control techniques, as well as the necessary capacitance and energy storage dimensions. The studies also recommend a technique for economic evaluation that emphasizes the expense of voltage sag events as well as the cost of investment in DVR with and without voltage sag events. The size of DVR and economic assessment model established in these studies enables industries to rate the cost of voltage sag and the total investment in mitigation devices.

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1. INTRODUCTION

Power quality refers to the elements of the power supply that have an impact on the functionality of modern industries processes. Unexplained equipment shutdowns or excursions, sporadic equipment damage or component failure, unpredictability in process performance regulation, arbitrary lockups and data errors, and power system component overheating are all predominantly attributable to poor power quality [1], [2]. These power quality problems can cause different impacts on different end users. For example, in order for an equipment to restart, a considerable time might be necessary (in the range of hours). This can lead to significant financial losses to industries [3]-[6]. Hence, end users' concern regarding power quality has become apparent when implications due to power quality are considered. Thus, the term "power quality" has become one of the top concerns in the power industry [1], [2], [7]. Attention has been dedicated to minimize the effect of poor power quality towards end users, notably within large industrial plants [8], [9].

Measuring the monetary damages resulting from power quality disruptions is a challenging undertaking. The extent of the customer's financial losses is contingent upon various factors, including the responsiveness of the equipment, the sensitivity of the process, and the intensity of the disturbances [10], [11]. Given the considerable ambiguity surrounding these variables, it is necessary to develop novel procedures, and methods to ensure the assessment remains consistent and the methodology remains practical. Therefore, to reduce power quality problems and subsequently the huge financial losses, mitigation devices have to be utilized.

According to recent studies, onsite problems contribute to 80-90% of all power quality issues, rather than utility difficulties [12], [13]. The most frequent types of voltage irregularities are harmonics, voltage sags, voltage swells, and short interruptions [13]. Voltage sag contributes to approximately 31% of all equipment interruptions. Another significant issue with power quality that results in unwanted tripping and the failure of sensitive machinery in industrial processes is voltage sags [12]. The crucial voltage sag characteristics are voltage magnitude and duration. In addition to the fault type and location, other factors that affect the voltage sag amplitude during an incident include pre-fault voltages, transformer connection, and fault impedance [14], [15]. When a network fault occurs, the resulting voltage sag will remain until protection devices operate to halt the flow of fault current. Due to a single voltage sag occurrence, the industries suffer tremendous losses in the number of millions of dollars [16]-[19]. There are two methods that have been developed to predict voltage sag events, namely monitoring and recording of voltage sag, and simulation of voltage sag [1], [10], [14]. The monitoring methods require longer monitoring time in order to obtain more accurate results. There are three main simulation methods that are used to assess voltage sags i.e. critical distance, fault position, and Monte Carlo [2], [17], [18]. Therefore, the study is to develop voltage sag assessment algorithms to predict the severity of voltage sag at a bus of interest in the transmission and distribution networks. The developed method is based on the quadratic interpolation method to determine the two values close to the critical points for the area of vulnerability.

Customers and utilities are becoming increasingly aware of power quality as there is a higher demand for high-quality, dependable power, and a greater number of distorting loads. As a result, it is critical to reduce the impact of voltage sags on sensitive equipment. Therefore, a mitigation device is used to reduce the severity of voltage sag, thus improving the power quality for the end user. There are many types of custom power mitigation devices which utilize power electronic [20]-[27]. The STATCOM and dynamic voltage restorer (DVR) are the equipment that is commonly used to address voltage sag [20]-[24]. Thus, these studies aim to use mitigation device is DVR. When the faults take place, the DVR injects a three-phase voltage to compensate for voltage sag to the nominal voltage. Hence, the consideration for correct sizing of the DVR is an important task due to cost reasons [28]-[31]. Therefore, it is important to develop a method that can calculate the appropriate or optimum sizing of DVR to mitigate voltage sag [30], [31].

It has been highlighted by many authors that voltage sag is the main cause of huge financial losses within the manufacturing or production sectors [32]-[37]. Hence, the study is to develop a financial assessment method to determine the benefit of DVR as well as losses due to voltage sag with and without a DVR. The developed method employs two-point crossover genetic algorithms. Therefore, it is important to consider the accurate assessment of financial losses due to voltage sag, so that a sound decision can be made for the investment of mitigation devices. Based on the above problems, it is imperative to develop a stochastic simulation method that can provide accurate estimation of the assessment of voltage sag, sizing of mitigation devices and perform financial analyses for utilities and end user. Therefore, this study aims to provide an economic assessment method based on optimization methodologies by using a two-point crossover genetic algorithm as the tool for voltage sag assessment and minimizing mitigation device cost.

2. METHODOLOGY

The first part of this study investigates voltage sags events caused by short-circuit and develops a stochastic assessment method. Second part of the study investigates alternative control strategies for DVR and implements a technique that provides for the analysis of suitable mitigation strategies and sizes for balanced and unbalanced faults at each location on buses or lines. The third part of the studies investigates the financial losses experienced by utilities and end consumers.

2.1. Voltage sag assessment

2.1.1. Remaining voltage determination at buses and lines

The Z-bus matrix can be used to determine the magnitude of the voltage sag at the bus and along the line when faults occur at a bus in a power system. The (1) and (2) used to calculate, if the faults take place on a bus and the line are given by [38]-[40].

$$V_m^{012} = V_m^{012pf} - [Z_{mi}^{012}]I_i^{012} \tag{1}$$

$$V_m^{012} = V_m^{012pf} - \left[Z_{mp}^{012}\right] I_p^{012} \quad (2)$$

2.1.2. Voltage sag compensation techniques by DVR

- Voltage sag compensation calculation

The DVR injects voltage according to the fault's location, nature, and impedance of the system. Different techniques are utilized by DVR to correct voltage sag [23], [24]. The pre-fault compensation technique is applied in this investigation. The (3) provides the load voltage relationship.

$$V_1 = V_{sag} + V_{DVR} \quad (3)$$

Where: V_l - load voltage, V_{sag} - voltage sag, and V_{DVR} - injected voltage by DVR.

- Reactive power injection

The power equation is as (4) and (5), when DVR injects only reactive power.

$$S_l = P_l + jQ_l \quad (4)$$

$$jQ = V_{DVR} + I_l \quad (5)$$

Where: Q: reactive power injected; S_l: load bus; and I_l: load current. The DVR's size and angle are determined by (6) and (7).

$$V_{DVR} = \sqrt{V_{pf}^2 + V_{sag}^2 - 2V_{pf}V_{sag}cos\theta} \quad (6)$$

$$\delta_{DVR} = \tan^{-1}\left(\frac{V_{sag}sin\theta}{V_{sag}cos\theta - V_{pf}}\right) \quad (7)$$

Where: V_{DVR}: injected voltage magnitude by DVR; δ_{DVR}: injected phase angle by DVR; V_{pf}: pre-fault voltage; and V_{sag}: voltage sag.

- Active power injection

The power equation is as in (8), when DVR injects only active power.

$$P = V_{DVR} + I_l \quad (8)$$

Where: Q: reactive power injected; S_l: load bus; and I_l: load current.

If reactive power fails to compensate for the voltage sag, active power injection continues restoration. After restoration with reactive power, various sag magnitude values can be obtained from (9). The DVR's size and angle are determined by (9).

$$V_{DVR} = \sqrt{V_{pf}^2 + V_{sag1}^2 - 2V_{pf}V_{sag1}cos\theta} \quad (9)$$

2.2. Genetic algorithm

The genetic algorithm (GA) is a problem-solving algorithm that may be modified to address a variety of issues. The GA parameters affect the computation time and overall efficiency. The process of computing GA is determined by population size, selection of value, crossover rate, mutation rate, and stop criteria. The size of the population is a crucial consideration in the establishment of a GA. Although GA may calculate populations of any size, an ideal population size would yield an ideal time. The method of selecting the best solution from a population establishes the level of superiority and is known as the selection value. The initial convergence is caused by superior individuals who heavily dominate inferior individuals, as indicated by the high selection value.

The crossover rate is defined as the percentage of solutions from a predefined population that can create offspring. The fraction of the population's total number of genes that determines how many new genes are introduced into the population for testing is known as the mutation rate, on the other hand. When the mutation rate is too low, a considerable portion of the solution space is not studied. The GA process's stopping point is defined by stop criteria. The GA will not be able to find enough solutions to find a universal solution if the process ends too soon. In contrast, if the analysis takes too long, the computing time will increase. Most GA systems use finishing criteria that are a defined number of generations or iterations reached.

2.2.1. Voltage sag compensation techniques by DVR

The methodology used to assess the optimum cost of investment by utilities or end-users to determine financial decisions is depicted in Figure 1. The following procedures can be used to describe Figure 1:

- The initial population has been generated to ensure uniform distribution. A string of 0 s and 1 s is used to represent the chromosome bits, and each bit of a chromosome is described by a gene.
- For each individual population, the financial equation is used to compute the fitness value.
- The population's target function is determined at two crossover points using the roulette wheel method.
- The two-crossover point process will detect every gene and crossover between two different parents to produce a pair of chromosomes. This can be resolved by exchanging genes between the two parents. From each set of parents, crossover points are produced at random.
- Individual population mutations are mutated as a result of crossover.
- Generate the best-fit value from the population for everyone's convergence point.
- The previous processes will be performed until the best convergence point is reached.
- After an iteration, the genetic algorithm terminates when a constant value is attained.

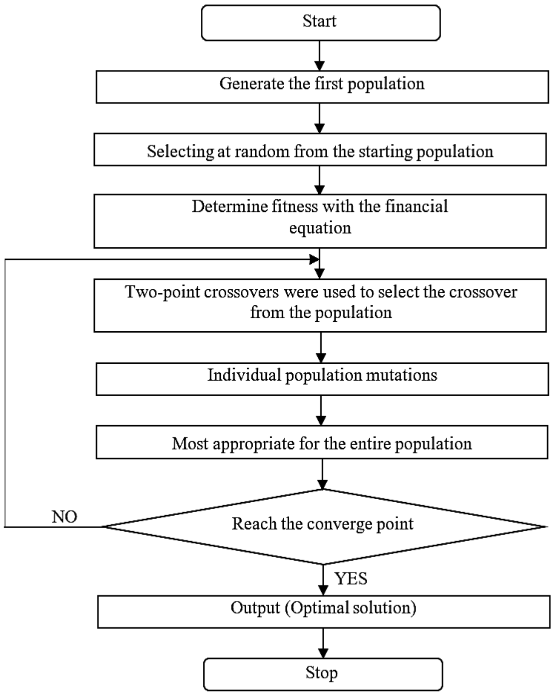

Figure 1. Proposed method of two-point crossover genetic algorithm

2.3. Assessment methods of financial losses

According to this investigation, all phases' affected magnitude ranges are less than 0.9 p.u. This reflects the assumption that not all voltage sags will cause an instrument of equipment or a process to fail. Additional research is being done to analyses the price of voltage sags based on voltage sag events. The type of industry is dependent on voltage sags, as indicated in Table 1, which also includes the cost of customer interruption. Total cost of voltage sag and DVR is calculate using (11) and (12).

$$C_T = \sum_{i=1}^{S_m}(V_m \times C_i) \tag{11}$$

$$C_{DVR} = 553(0.0004S_{DVR}^2 - 0.3225S_{DVR} + 128.75)(\frac{RM}{MVar}) \tag{12}$$

Where: C_T: voltage sag total cost; C_i: voltage sag cost; V_m: number of events by voltage sag; C_{DVR}: DVR cost; and S_{DVR}: DVR power rated.

Conventional financial methods derived from principles like payback time (PBT) and net present value (NPV) are used in the economic assessments of power quality changes and the ensuing installation of mitigating devices. The (13) and (14) are applied to calculate the PBT and NPV.

$$PBT = \frac{C_i}{C_a} \quad (13)$$

$$NPV = \sum_{n=0}^{N} \frac{C_a}{(1+r)^n} - C_i \quad (14)$$

Where: C_i: initial investment cost of DVR (cost of DVR + installation cost); and C_a: annual expenses cost; and r: discount counted rate of a product; n: number of years for the product; and N: investment of a lifetime.

Table 1. Assumed cost of per voltage sag events [6], [7]

Consumer	Cost of sag/event
Residential load	-
Commercial load	1 k
Industrial load	16.3 k
Large user load	581 k

3. RESULTS AND DISCUSSION

The developed algorithm is used to simulate faults for all buses and is applied to the IEEE RTS-24 bus test system as illustrated in Figure 2 to compare the feasibility of the system with and without DVR. This system comprises 24 buses, 33 lines connecting them, 11 power generating stations, and five transformers connected, and the information of the system is provided in [41]. All generators have internal impedances of j0.05, j0.2, and j0.3 for the positive, zero, and negative sequences, respectively.

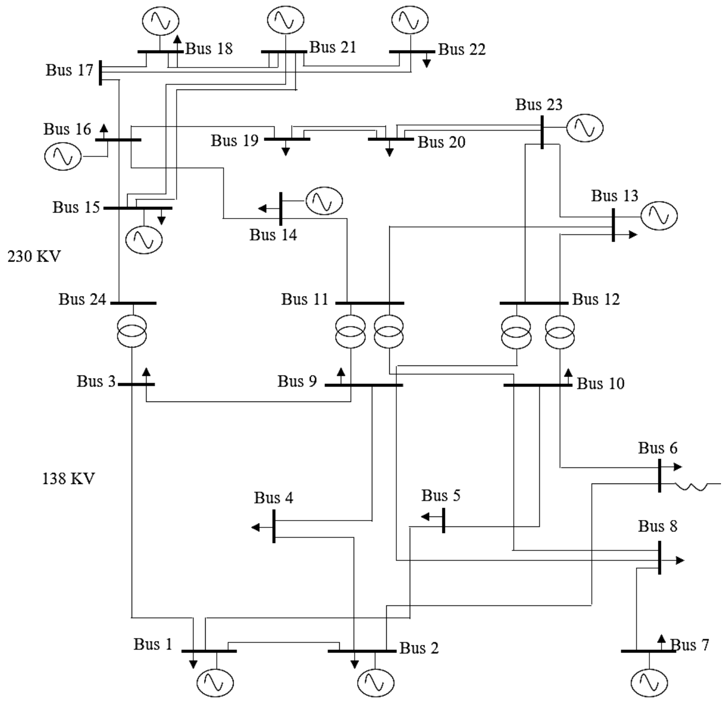

Figure 2. IEEE RTS-24 busses test system

The responses of voltage sag and voltage magnitude with and without DVR are demonstrated by simulation using MATLAB. The results of the study were verified using simulations with a phase shift of 30° and a maximum voltage magnitude drop of 50%. As a result, the voltage on buses is shown to range from 0.1 p.u. to 0.9 p.u. The evaluation of voltage sag and mitigation device financial losses is the final process. Bus 4 is being studied to investigate the behavior of voltage sag magnitudes for various fault types and problem locations.

It is observed that results obtained by previous studies [1], [15], [37]-[39] using the analytical method and fault position method differ significantly from the results using the quadratic interpolation techniques. In the analytical method, since only one location of fault position point is considered within the transmission line, this poses a disadvantage in terms of accuracy. Therefore, in these studies the quadratic interpolation technique is used to achieve two locations of fault position points within the transmission line. The following procedures describe the techniques used in this study to predict voltage sag more accurately for large system networks:

- Calculation of pre-fault voltages is done along with sequence admittance matrices for each fault type.
- Z_{Bus} impedance matrices algorithms are formulated for positive, negative, and zero sequences for each type of fault.
- Magnitude of voltage for different types of faults (SLGF, LLF, DLGF, and 3PF).
- The threshold voltage level is capped for the ITIC or CBEAM curve (nominal value of 0.5-0.7 p.u).
- Calculate the voltage sag magnitude for the system network.
- Set the range of voltage sag magnitude to plot the actual curve, by selecting the voltage sag magnitude range at q=0, q=0.5 and q=1, for a particular type of fault.
- When an equation is calculated, the magnitude of the voltage sag is plotted.
- If the voltage threshold is lower than the magnitude of the voltage sag at both q=0 and q=1, then this line is higher than the threshold nominal value of 0.7 p.u.
- As the voltage threshold exceeds the maximum magnitude of the remaining voltage equation for $0 \leq q < 1$, this line falls below the threshold nominal value of 0.7 p.u.
- If the voltage threshold is less than the maximum magnitude of the remaining voltage equation for $0 \leq q \leq 1$ and greater than the voltage sag magnitudes at both q=0 and q=1, it suggests two critical sites are on the line.
- Finally, the total number of voltage sags can be computed by adding the estimated voltage sags for each network line.

3.1. Assessment of voltage sag

The focus of this study is to demonstrate the ability of the proposed approach in lowering balanced and unbalanced faults by taking into consideration various types of faults. Table 2 contains a list of the sag duration times needed to clear the faults in the case studies. The three-dimensional bar chart in Figure 3 depicts the total number of voltage sags that occur yearly for three phase fault (3PF) buses in terms of magnitude and duration of the voltage. The x and y axes, which indicate all the buses, and the voltage sag magnitude range and the z axis, which shows the quantity of voltage sag magnitude. The following colours are used to show the various voltage duration levels: 60 ms is by blue, 80 ms by green, 150 ms by yellow, and 300 ms by red.

Table 2. Fault clearing time [6], [7]

Voltage level	Fault clearing time
Bus faults	60 ms
132 kV	80 ms
33 kV	150 ms
11 kV	300 ms

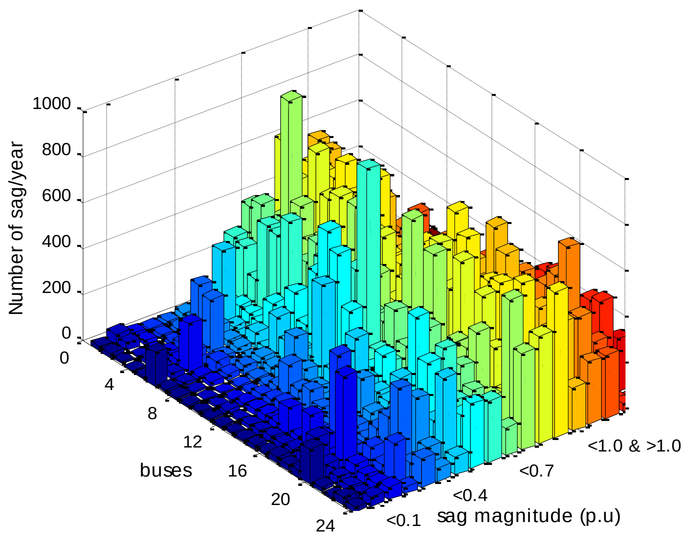

Figure 3. Voltage sag at bus 4 when the faults at lines 2-6

Figure 3 depicts the remaining voltage level for all 24 buses on the system network when the faults take place on line 2–6. As can be observed from Figure 3, voltage magnitudes on the bus are less disrupted when faults occur on lines that are farther from the bus. Voltage drops dramatically when failures are on lines near the bus.

Figure 3 depicts the total number of voltage sags for all four categories of failures at various degrees of magnitude and duration for all buses. The total number of voltage sag losses caused by the three-phase fault is 1498.

The number of voltage sags at the worst effect phases for all buses for single-line to ground fault (SLGF) and 3PF are shown in Figure 4. As can be observed, in the instance of SLGF, bus numbers 4 and 21 experience the highest and lowest yearly voltage sag rates which are 2425 and 893, respectively. The voltage drops for 3PF at buses 4 and 21, which are 1496 and 496, respectively. All buses have values that are less than 1500.

In this study, different types of faults are considered to show the potential of quadratic interpolation techniques over the analytical methods in dealing with balanced and unbalanced faults. For cases of SLGF, double line-to-ground fault (DLGF), line-to-line fault (LLF), and 3PF in Figure 5, the variation in a number of voltage sags can be described as exponential. The interpolation method has been compared with an analytical method [37]. These two methods (analytical and interpolation) are comparable as both show a similar number of voltage sag in Figure 5. For all the fault conditions, the analytical methods yielded almost similar voltage sag magnitudes, but the interpolation method exhibited a continuously higher value than the analytical methods. As an example, in the case of SLGF, the highest percentage difference in terms of the number of voltage sag was found to occur at the magnitude of 0.3 p.u. and 0.4 p.u. with a difference of 28.6% and 29.2%, respectively. The roots of the interpolation curve are used to determine the two possible fault location points. The interpolation method is shown to yield a more accurate number of voltage sag per year for SLGF, LLF, DLGF, and 3PF for sensitive customers located at bus 4. The interpolation method was also shown to be more accurate by 5% for SLGF, 10% for LLF, 11% for DLGF, and 3PF when compared to analytical methods. Therefore, it can be concluded that for all the systems evaluated, the interpolation method showed the highest value in terms of the number of voltage sag as compared to the analytical methods. Moreover, the proposed method is able to calculate the exact fault position along the line for a specified voltage sag magnitude.

3.2. Assessment of DVR sizing

Proper sizing of DVR had to be calculated to reduce the severity of voltage sag in the system network and to maintain voltage magnitude at particular buses, as well as the whole network. Therefore, the cost of installation of a DVR device could be largely reduced in the system network. The injection of voltage by DVR depends on fault type, location, and system impedance. A number of important procedures that were considered before the injection of voltage magnitude was carried out are: i) All voltages were balanced before the occurrence of a fault; hence, negative and zero sequences had been zero; ii) In the event when a fault took place, reactive power was injected to compensate the magnitude of voltage; iii) In the case when the reactive power could not fully compensate the voltage magnitude, active and reactive power shall be injected; and iv) DVR devices should restore the bus voltage to its pre-fault voltage magnitude and angle.

The (3)-(7) can be used to determine the sizing of DVR, and the results are shown in Figure 6. For the network system shown in Figure 2, faults are simulated for worst-case phases of buses with and without DVR, and voltage sag magnitudes are computed and shown in Figure 6. The output reveals the bus faults and voltage magnitudes between 0.1 and 0.9 p.u. According to the DVR's selected rating, the voltage magnitude from 0.5 p.u. and a ±30^o phase shift can be restored to a pre-fault voltage of 1.0 p.u. The degree of voltage that can be restored depends on the availability of reactive and active power.

To investigate the behavior of voltage sag magnitudes for various types of faults, bus 4 was investigated. A 40MVA DVR is connected when bus 4 is taken into consideration to determine how much it can contribute to restoring voltage sag. Assessment of the DVR is carried out using the two same size of apparent power (40MVA) with different power ratings of active and reactive power (35MW + j20Mvar and 5MW + j40Mvar) to investigate the performance of the DVR size. Figure 5 depicts an analysis of the voltage magnitude with and without DVR based on 24 buses.

Figure 6 shows the three scenarios with and without DVR that were employed on the 24-bus system to investigate the fault at bus number 4. As can be observed when comparing the histogram plots, bus number 4 was identified to have the lowest voltage magnitude value of 0.132 p.u. When using the same bus with a DVR and the active and reactive power ratings of 5MW + j40Mvar in scenario 1, this value climbed to 0.223 p.u. This is an increase of 9%, while in scenario 2, where active and reactive power is rated at 35 MW + j20 Mvar, the value grew to 0.705 p.u, representing a 27% increase.

According to Figure 6, the magnitude of the voltage ranged from 0.132 p.u. to 0.863 p.u. (0.731 p.u.) in the event that there was no DVR. This value decreased in scenario 1 with DVR, as shown in Figure 5, from 0.941 p.u. to 0.223 p.u. (0.718 p.u.) and shows a 1.3% decrease. This value decreased in scenario 2 to between 0.705 p.u. and 0.961 p.u. units (0.256 p.u.), as shown in Figure 5. This results in a 48% drop in voltage magnitude. Without DVR, the average was 0.546 p.u.; with DVR, the average was 0.639 p.u. for scenario 1 and 0.821 p.u. for scenario 2. This demonstrates that, in terms of the probability of reaching the voltage threshold, the average injected power increased by 9% for scenario 1 and by 28% for scenario 2.

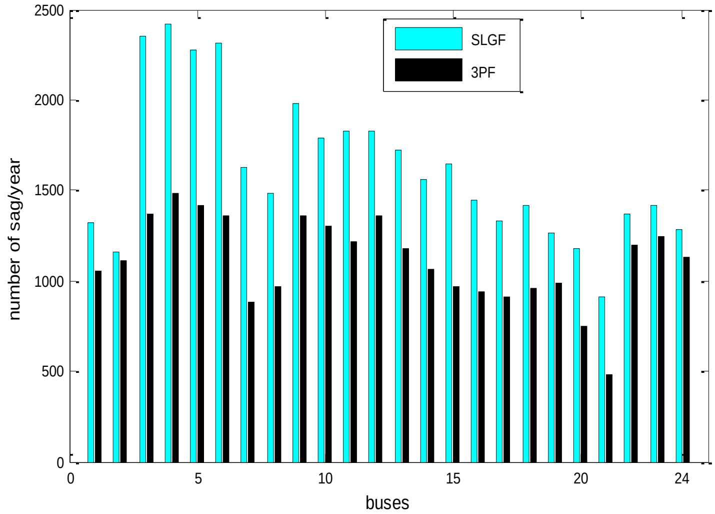

Figure 4. Number of voltage sags due to SLGF and 3PF

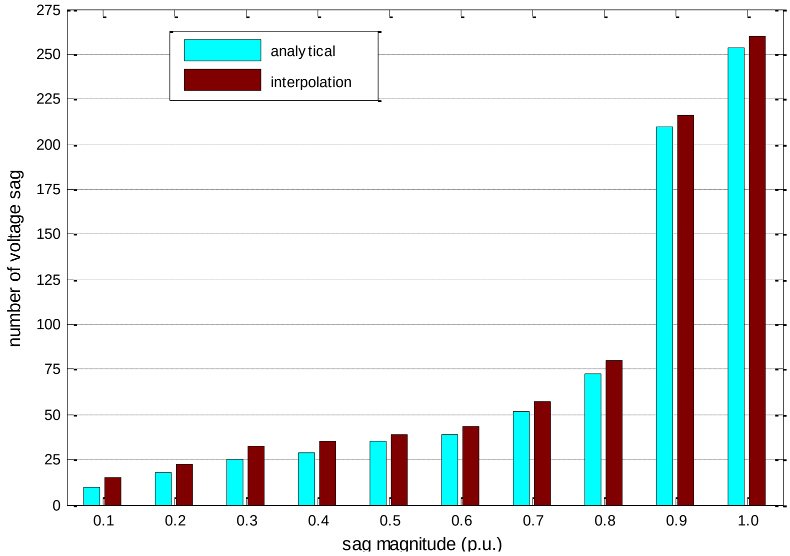

Figure 5. Comparison single line-to-ground fault

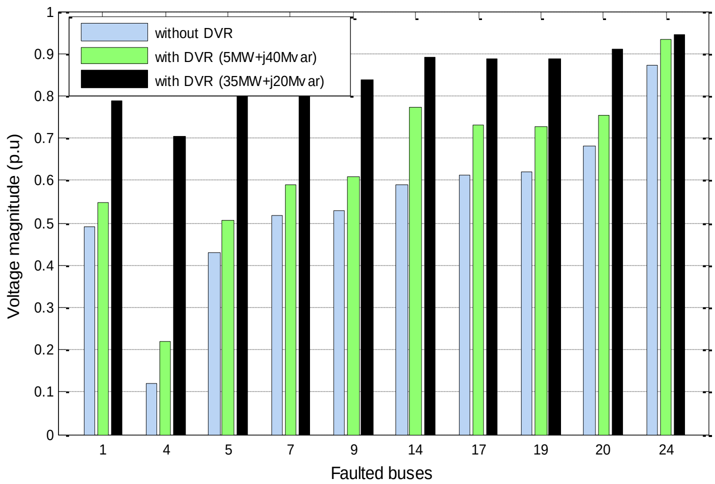

Figure 6. Voltage sag magnitudes at bus 4 with and without DVR for three-phase fault

3.3. Voltage sag with and without DVR

To evaluate voltage sag performance with and without DVR, DVR is placed within the power system network. Figure 7 shows the three-dimensional bar chart to represent the number of voltage sag per year for all the buses for 3PF with respect to the voltage magnitude and voltage duration. The x and y axis represent all the buses and the voltage sag magnitude range respectively while the number of voltage sag magnitude is represented by the z axis. Different colors are used as: (blue is 0 - 0.2 s, green 0.2 – 0.4 s, yellow 0.4 – 0.6 s, and red 0.6 – 0.8 s) to indicate the different voltage durations. When a fault occurs at lines 2-6, the voltage sag performance of the entire network of all the buses are as shown in Figure 7. When the faults occur in lines that are further from the bus, voltage magnitudes on the bus are less disturbed, as shown in Figure 7. When the faults are on lines close to the bus, voltage drops significantly. Faults below the magnitude of 0.85 p.u. are mitigated in this section. Bus 4 is selected for further investigation, and a 4 MVA DVR is connected to assess the effectiveness with which the voltage sag has been restored. In this scenario, the DVR size of active and reactive power used is (2.1342 MW + j3.3831 Mvar). To demonstrate the effectiveness of the total number of voltage sags in a specific voltage magnitude range faulty buses for all four types of faults are investigated, and the results are presented just for the 3PF in Figure 7. The total number of voltage sag losses caused by the three-phase fault without DVR is 1498 and the number of voltage sag losses dropped to 685 with DVR.

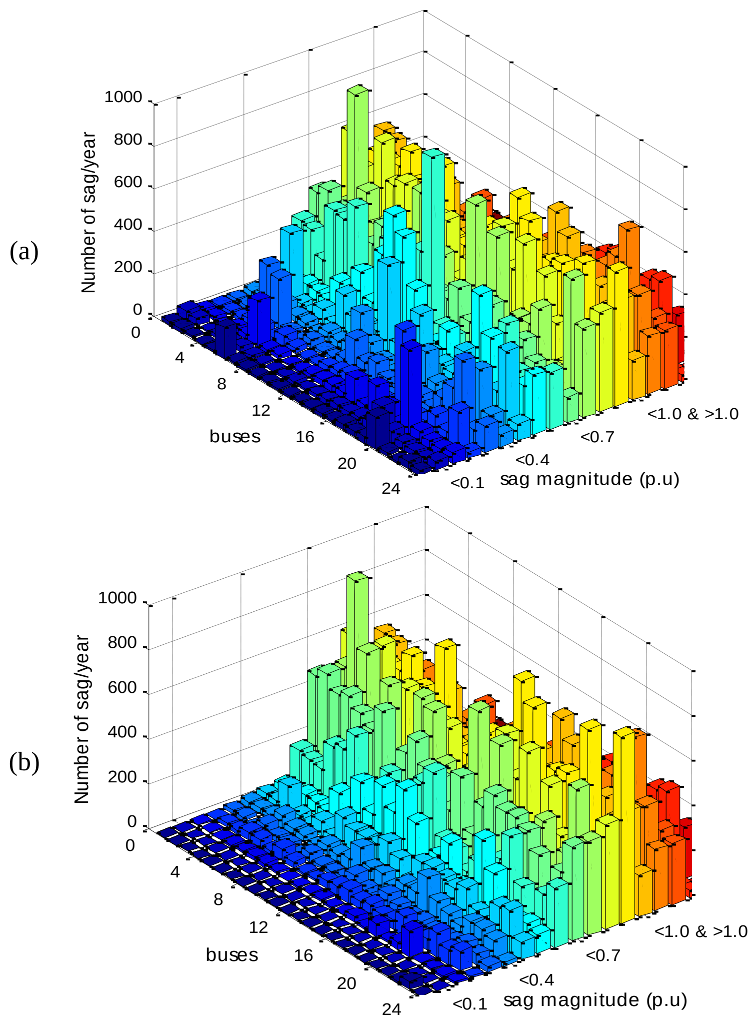

Figure 7. Number of voltage sag with and without DVR for three phase faults:
(a) without DVR and (b) with DVR

3.4. Financial assessment

The proposed method is a financial assessment method based on genetic algorithm using two-point crossovers to assess the optimum point of voltage sag. The details of the financial assessment method are described as:

- Initialize: The number of voltage sag events obtained was initialized.
- GA process: GA process was employed to identify the optimal point of voltage sag, which could minimize the financial losses of voltage sag and DVR.
- Costs of voltage sag and DVR: The cost of voltage sag was calculated based on the GA optimum point, while the cost of DVR was determined from the given equation.
- Graphical results: The optimum number of voltage sags, as well as costs of voltage and DVR, is displayed via two-dimension bar chart and pie chart.

3.4.1. Voltage sag cost assessment

The (11) and (12) can be used to determine the cost of voltage sag, and the results are shown in Figure 8. As shown in Figure 6, there are a total of 1422 voltage sags below 0.9 p.u., of which 461 have magnitudes below 0.5 p.u., 478 have magnitudes between 0.5 and 0.7 p.u., and 483 have magnitudes between 0.7 and 0.9 p.u. However, voltage sags of more than 0.9 p.u. (59.88%) will not damage industrial equipment. Figure 8 shows that the losses caused by the voltage sag in the network have a mean of RM 15.848 million.

3.4.2. DVR cost assessment

The cost of the mitigation technique can be calculated by applying (11) and (12), where the maintenance costs are 10-15 percent of the DVR capital cost, the yearly share over the lifespan is 15 years, and a discount rate of 10% is used. Based on Figure 9, the first bar represents the cost of DVR of RM 0.045 million with a probability type of 3. From Figure 8, it can be seen that the second to the sixth bar chart represents probability types and cost of 5 (RM 0.067 million), 1 (RM 0.113 million), 4 (RM 0.128 million), 2 (RM 0.137 million), and 6 (RM 0.187 million), respectively. Hence, the total cost of the DVR applied in this network had been RM 0.677 million, as shown in Figure 9, while the maintenance cost is RM 0.068 million.

3.4.3. Voltage sag assessment cost with DVR

The cost of voltage sag losses with DVR is depicted in Figure 10. In total, there are 589 voltage sags below 0.9 p.u., of which 176 have magnitudes below 0.5 p.u., 194 have magnitudes between 0.5 and 0.7 p.u., and 219 have magnitudes between 0.7 p.u. and 0.9 p.u. According to Figure 9, the losses due to voltage sag in the network have a mean value of RM 10.284 million. However, based on the study above, it can be concluded that after the installation of a DVR, the number of voltage sag losses decreased to 589 from 1422. Figure 10 depicts the cost of voltage sag performance inside the network using multimodal genetic algorithm approaches with and without DVR. As demonstrated in Figure 11, the number of voltage sags dropped significantly in the first ten generations from 1422 to 1106, decreased gradually from 1126 to 589, and then stabilized at 851 in the final fifteen generations. However, it can be concluded from the studies described above that the percentage of voltage sag decreased to 35.12% of the base voltage sag following the installation of mitigation devices (DVR).

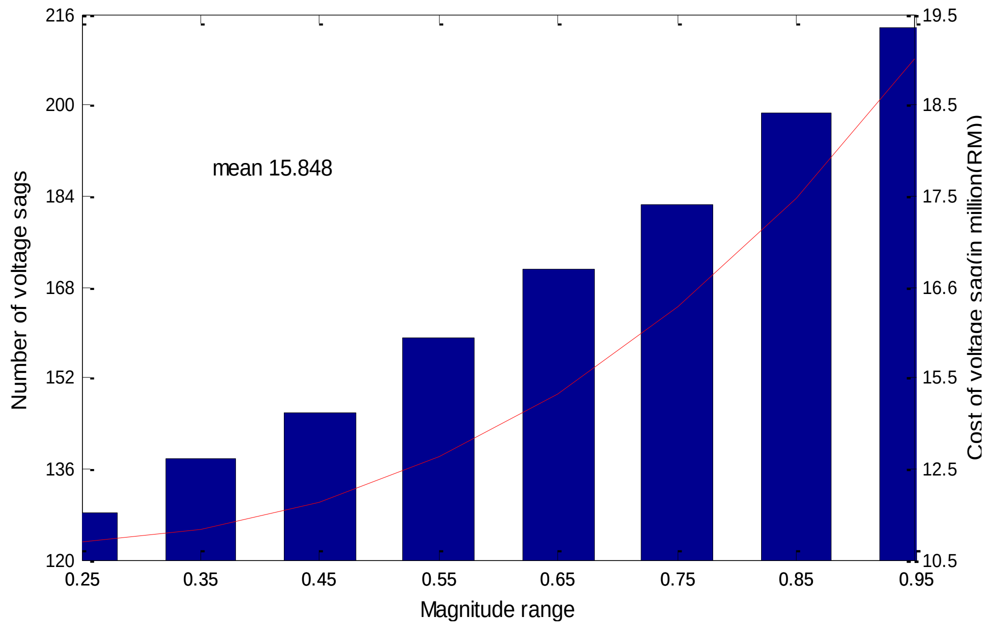

Figure 8. Voltage sag cost

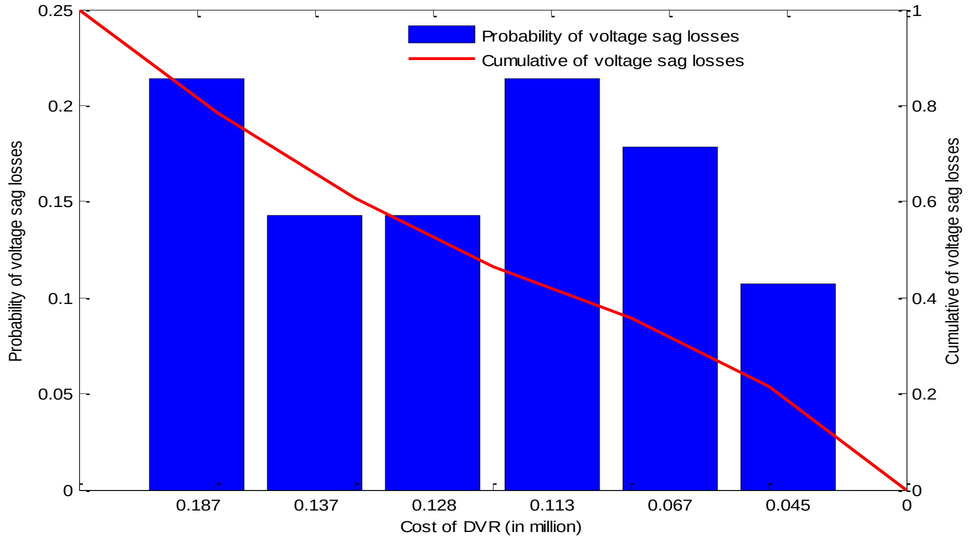

Figure 9. DVR cost

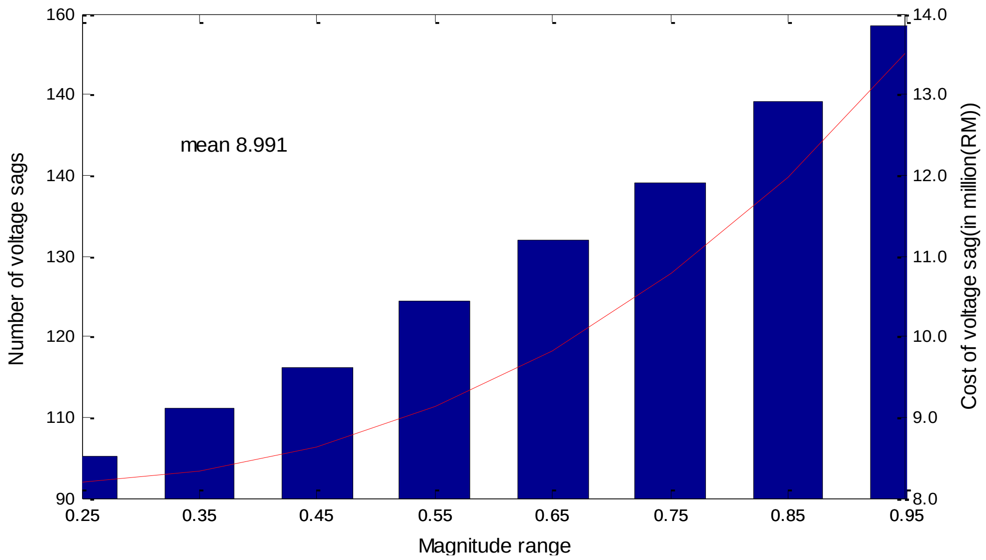

Figure 10. Voltage sag cost with DVR

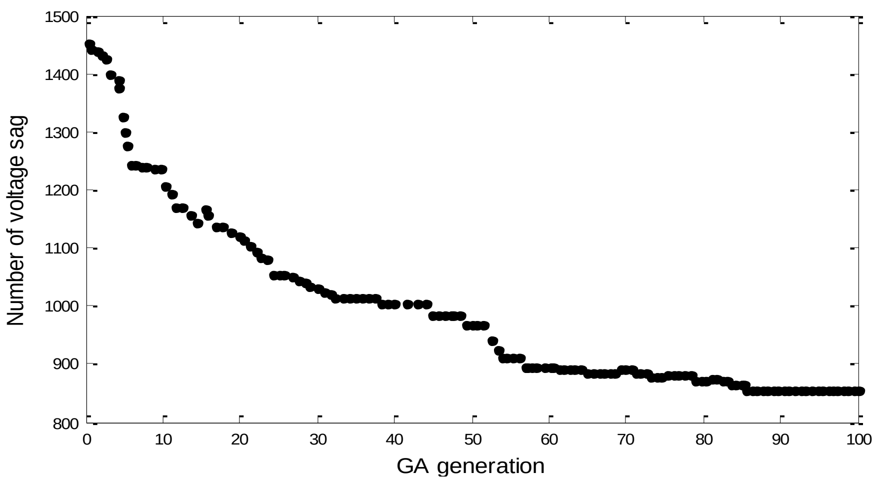

Figure 11. Voltage sag losses convergence

3.4.4. Assessment of payback time

The payback time (PBT) represents the duration required for a project to recoup its initial expenditure and may be determined by utilizing (13). Customers want to invest in projects that have a short payback period. To calculate the payback period, the investor must first assess the total cost of the investment, including the whole upfront cost, annual savings, as well as operational costs. The payback period is calculated by dividing the initial cost total by the yearly charges and this can be calculated by (13). The voltage sag without DVR is RM 15.848 million per year, according to Figure 6. As observed in Figure 9, the average annual loss is RM 10.284 million, which is less than it would be if any mitigation measures were not taken. A total payback duration of less than 2.13 years is depicted in Table 3 based on the PBT analysis.

Table 3. Payback time analysis (in million (RM))

Cost	Without DVR	With DVR
Voltage sag cost	15.848	10.284
Device's cost	0	8.991
Maintenance cost	0	1.349
Total cost	15.848	
Saving cost	15.848–10.284=5.564	
Capital cost	8.991	
Payback time	8.991/(5.564–1.349)=2.13	

3.4.5. Assessment of net present value

The net present value (NPV) method is used to calculate the lifetime cash flows of a project. The organization will pick all projects with a positive NPV regardless of the amount of capital required. The cash flows that are involved are the cost of initial investment, cost of maintenance, and standby expenses on the adverse side and the avoided costs on the favorable side. A DVR initially requires a substantial investment cost, but over a period of its lifespan, it will offer years of voltage support with just minor partial maintenance costs. From (14), it is possible to determine the net present value of these cash flows.

The discounted cash flow must be calculated because it is known that the benefit only occurs over a specific time period. Devices are projected to last for 15 years, and the discounted rate is 15%. Based on Figure 12 (NPV), it can be concluded that is more desirable due to the enormous financial gain that is accruing over time. This option was chosen over the others because it starts to pay off four years after the original investment. After the fourth year, a positive value is obtained, and after 15 years after installation, the NPV increases to 15.75 million.

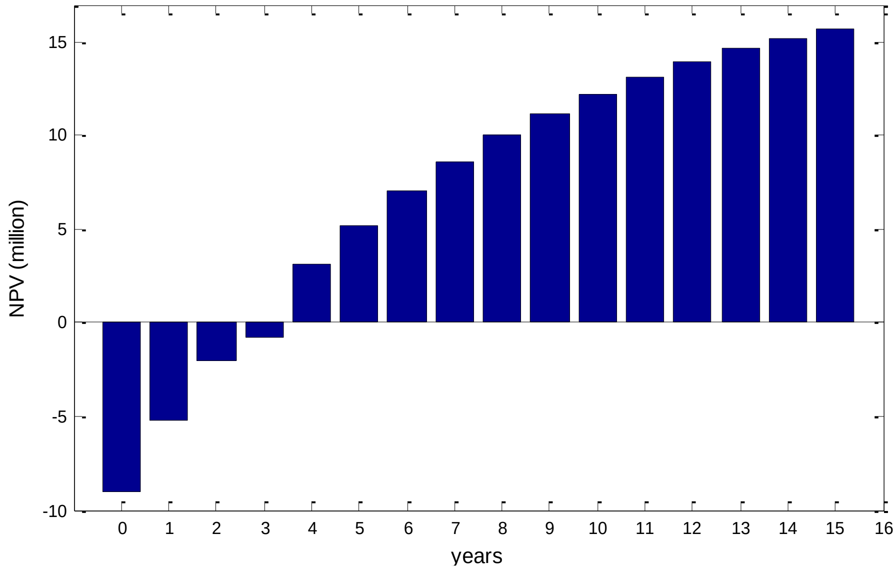

Figure 12. Assessment of net present value

Figure 13 depicts the GA optimization's convergence characteristics. As expected, the NPV rises with the number of generations. Each solution in the optimization process needs to be assessed and given a mathematical model, which can then be converted into fitness values to serve as the basis for choosing individuals for a new population. When it comes to GA optimization, the evaluation function is crucial, and how these functions are designed can have a big impact on how well the result turns out.

Therefore, understanding how to build the mathematical model that best illustrates a concept is important. Because there are no empirical studies that compare the relative merits of different solutions, the variances in results demonstrate that the choice of solution is still, at least in part, a question of human judgment. More computation is required. All the GA used in this study use a maximum of 100 generations, which is adequate to get a converged outcome.

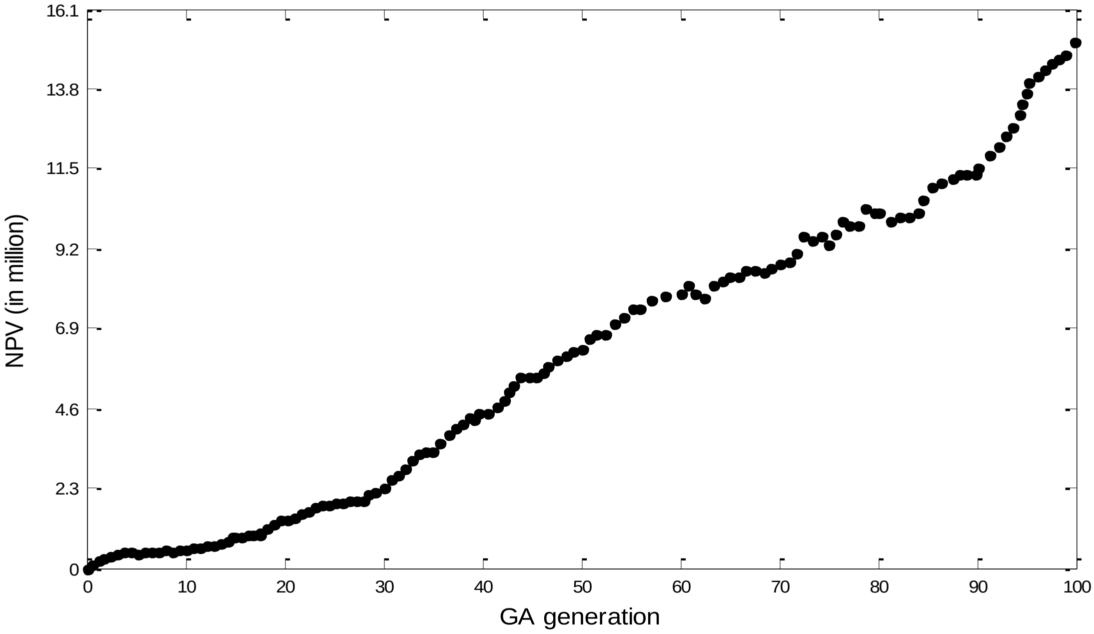

Figure 13. Net present value convergence

4. CONCLUSION

In this paper, the voltage sag magnitudes at various buses were predicted for faults at random location on a transmission and distribution network. Three main tasks or stages were performed i.e. stochastic assessment of voltage sag, sizing of mitigation device, and lastly the financial implications. A stochastic assessment algorithm was programmed in MATLAB to carry out the voltage sag analysis within an IEEE 24-bus network. The fault calculation procedure which includes modelling the system impedance matrix, formulating fault current for all types of faults (bus or line faults) and developing sequence components were included in this stage. The voltage sag severity throughout the network was illustrated using 3D bar charts. The stochastic assessment method demonstrated a significant improvement in the accuracy of predicting the severity of voltage sag by 8% as compared to the analytical method.

DVR is used to restore the voltage sag magnitude to its nominal voltage. A mathematical model was developed to determine the size of mitigation devices (DVR). The effectiveness of the three different control methods to facilitate the sizing of DVR was investigated for different types of faults, fault severity, and load. From the calculation of real and reactive power, the amount of voltage and current injection which is proportional to the active power and reactive power exchange by DVR can be obtained. This can assist industries to determine the appropriate sizing for the DVR model.

The GA method was developed based on optimization using two-point crossovers. The optimum cost for voltage sag and mitigation devices was determined. This optimum cost points towards the appropriate investment in a mitigation device needed by the end-user. Financial analysis tools such as payback time and net present value were used to calculate the recovering time for the investment of mitigation devices. A comprehensive assessment method has been developed to identify voltage sag events, sizing of mitigation device, and investments cost for mitigation device. Overall, the results presented in this thesis provide a methodology for industries to perform financial analysis on the investment of mitigation devices.

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REFERENCES

[1] M. H. Bollen, "Understanding Power Quality Problems: Voltage Sags and Interruptions," in *Wiley-IEEE Press*, IEEE Xplore, 2000, p. 672. [Online]. Available: https://ieeexplore.ieee.org/book/5270869
[2] R. C. Dugan, M. F. McGranaghan, and H. W. Beaty, *Electrical power systems quality*. New York, NY: McGraw-Hill, 1996.
[3] R. Targosz and J. Manson, "Pan-European power quality survey," in *2007 9th International Conference on Electrical Power Quality and Utilisation*, Barcelona, Spain: IEEE, Oct. 2007, pp. 1–6. doi: 10.1109/EPQU.2007.4424203.
[4] D. Chapman, "The cost of poor power quality," in *Power quality application guide*, Copper Development Association, 2001.
[5] F. C. Pereira, O. C. N. Souto, J. C. De Oliveira, A. L. A. Vilaca, and P. F. Ribeiro, "An analysis of costs related to the loss of power quality," in *8th International Conference on Harmonics and Quality of Power. Proceedings (Cat. No.98EX227)*, IEEE, 1998, pp. 777–782. doi: 10.1109/ICHQP.1998.760141.
[6] Electric Power Research Institute (EPRI) Inc., "The cost of power disturbances to industrial and digital economy companies June 2001 ID: 1006274," California, 2013. [Online]. Available: https://www.epri.com/research/products/3002000476
[7] H. D. Keulenaer, "Power quality self-assessment guide," in *Power quality application guide*, Copper Development Association, 2002.
[8] R. Lamedica, A. Patrizio, A. Prudenzi, E. Tironi, and D. Zaninelli, "Power quality costs and upgrading solutions: the energy centre," in *Ninth International Conference on Harmonics and Quality of Power. Proceedings (Cat. No.00EX441)*, IEEE, 2000, pp. 691–696. doi: 10.1109/ICHQP.2000.897762.
[9] S. Z. Djokis, K. Stockman, J. V. Milanovic, J. M. Desmet, and R. Belmans, "Sensitivity of AC adjustable speed drives to voltage sags and short interruptions," *IEEE Transactions on Power Delivery*, vol. 20, no. 1, pp. 494–505, Jan. 2005, doi: 10.1109/TPWRD.2004.832353.
[10] S. Z. Djokic, J. V. Milanovic, D. J. Chapman, M. F. McGranaghan, and D. S. Kirschen, "A new method for classification and presentation of voltage reduction events," *IEEE Transactions on Power Delivery*, vol. 20, no. 4, pp. 2576–2584, Oct. 2005, doi: 10.1109/TPWRD.2005.852322.
[11] S. Z. Djokic, J. V. Milanovic, and D. S. Kirschen, "Sensitivity of AC coil contactors to voltage sags, short interruptions, and undervoltage transients," *IEEE Transactions on Power Delivery*, vol. 19, no. 3, pp. 1299–1307, Jul. 2004, doi: 10.1109/TPWRD.2004.824396.
[12] M. T. Aung, J. V. Milanovic, and C. P. Gupta, "Propagation of asymmetrical sags and the influence of boundary crossing lines on voltage sag prediction," *IEEE Transactions on Power Delivery*, vol. 19, no. 4, pp. 1819–1827, Oct. 2004, doi: 10.1109/TPWRD.2004.835427.
[13] I. Hunter, "Power quality issues: a distribution company perspective," *Power Engineering Journal*, vol. 15, no. 2, pp. 75–80, Apr. 2001, doi: 10.1049/pe:20010203.
[14] B. Wang, W. Xu, and Z. Pan, "Voltage sag state estimation for power distribution systems," *IEEE Transactions on Power Systems*, vol. 20, no. 2, pp. 806–812, May 2005, doi: 10.1109/TPWRS.2005.846174.
[15] B. Polajžer, G. Štumberger, and D. Dolinar, "Impedance-based methods for detection of voltage sag sources," *Renewable Energy and Power Quality*, vol. 10, no. 10, pp. 1255–1258, Apr. 2012, doi: 10.24084/repqj10.671.
[16] M. F. Mc Granaghan, D. R. Mueller, and M. J. Samotyj, "Voltage sags in industrial systems," *IEEE Transactions on Industry Applications*, vol. 29, pp. 397–403, 1993, doi: 10.1109/28.216550.
[17] J. V. Milanovic and C. P. Gupta, "Probabilistic assessment of financial losses due to interruptions and voltage sags—part I: the methodology," *IEEE Transactions on Power Delivery*, vol. 21, no. 2, pp. 918–924, Apr. 2006, doi: 10.1109/TPWRD.2006.870988.
[18] J. V. Milanovic and C. P. Gupta, "Probabilistic assessment of financial losses due to interruptions and voltage sags—part II: practical implementation," *IEEE Transactions on Power Delivery*, vol. 21, no. 2, pp. 925–932, Apr. 2006, doi: 10.1109/TPWRD.2006.870987.
[19] M. Mc Granaghan and B. Roettger, "Economic evaluation of power quality," *IEEE Power Engineering Review*, vol. 22, no. 2, pp. 8–12, Feb. 2002, doi: 10.1109/MPER.2002.981339.
[20] S. Chen and G. Joos, "Series and shunt active power conditioners for compensating distribution system faults," in *2000 Canadian Conference on Electrical and Computer Engineering. Conference Proceedings. Navigating to a New Era (Cat. No.00TH8492)*, IEEE, 2000, pp. 1182–1186. doi: 10.1109/CCECE.2000.849650.
[21] A. Ghosh and G. Ledwich, "Compensation of distribution system voltage using DVR," *IEEE Transactions on Power Delivery*, vol. 17, no. 4, pp. 1030–1036, Oct. 2002, doi: 10.1109/TPWRD.2002.803839.
[22] C. Benachaiba and B. Ferdi, "Power quality improvement using DVR," *American Journal of Applied Sciences*, vol. 6, no. 3, pp. 396–400, Mar. 2009, doi: 10.3844/ajas.2009.396.400.
[23] M. H. Haque, "Compensation of distribution system voltage sag by DVR and D-STATCOM," in *2001 IEEE Porto Power Tech Proceedings (Cat. No.01EX502)*, IEEE, 2001, p. 5. doi: 10.1109/PTC.2001.964609.
[24] V. K. Ramachandaramurthy, C. Fitzer, A. Arulampalam, C. Zhan, M. Barnes, and N. Jenkins, "Control of a battery supported dynamic voltage restorer," *IEE Proceedings - Generation, Transmission and Distribution*, vol. 149, no. 5, pp. 533–542, 2002, doi: 10.1049/ip-gtd:20020658.
[25] A. Sannino, M. G. Miller, and M. H. J. Bollen, "Overview of voltage sag mitigation," in *2000 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.00CH37077)*, IEEE, 2000, pp. 2872–2878. doi: 10.1109/PESW.2000.847340.
[26] H. Zhang and T. He, "Optimization model of urban rail transportation planning based on evolutionary algorithm of state space model," *Computer-Aided Design and Applications*, vol. 21, no. S3, pp. 211–225, Aug. 2024, doi: 10.14733/cadaps.2024.S3.211-225.
[27] A. Ghosh and G. Ledwich, *Power quality enhancement using custom power devices*. Boston, MA: Springer US, 2002. doi: 10.1007/978-1-4615-1153-3.
[28] S. S. Choi, J. D. Li, and D. M. Vilathgamuwa, "A generalized voltage compensation strategy for mitigating the impacts of voltage sags/swells," *IEEE Transactions on Power Delivery*, vol. 20, no. 3, pp. 2289–2297, Jul. 2005, doi: 10.1109/TPWRD.2005.848442.

[29] C. J. Melhorn, A. Braz, P. Hofmann, and R. J. Mauro, "An evaluation of energy storage techniques for improving ride-through capability for sensitive customers on underground networks," *IEEE Transactions on Industry Applications*, vol. 33, no. 4, pp. 1083–1095, 1997, doi: 10.1109/28.605752.
[30] H. J. Kim *et al.*, "3 MJ/750 kVA SMES system for improving power quality," *IEEE Transactions on Applied Superconductivity*, vol. 16, no. 2, pp. 574–577, Jun. 2006, doi: 10.1109/TASC.2006.871329.
[31] D. Van Hertem, M. Didden, J. Driesen, and R. Belmans, "Choosing the correct mitigation method against voltage dips and interruptions: a customer-based approach," *IEEE Transactions on Power Delivery*, vol. 22, no. 1, pp. 331–339, Jan. 2007, doi: 10.1109/TPWRD.2006.881456.
[32] S. Bahadoorsingh, J. V. Milanovic, Y. Zhang, C. P. Gupta, and J. Dragovic, "Minimization of voltage sag costs by optimal reconfiguration of distribution network using genetic algorithms," *IEEE Transactions on Power Delivery*, vol. 22, no. 4, pp. 2271–2278, Oct. 2007, doi: 10.1109/TPWRD.2007.899524.
[33] P. Heine, P. Pohjanheimo, M. Lehtonen, and E. Lakervi, "A method for estimating the frequency and cost of voltage sags," *IEEE Transactions on Power Systems*, vol. 17, no. 2, pp. 290–296, May 2002, doi: 10.1109/TPWRS.2002.1007895.
[34] C. P. Gupta and J. V. Milanovic, "Costs of voltage sags: Comprehensive assessment procedure," in *2005 IEEE Russia Power Tech*, IEEE, Jun. 2005, pp. 1–7. doi: 10.1109/PTC.2005.4524795.
[35] C. P. Gupta, J. V. Milanovic, and M. T. Aung, "The influence of process equipment composition on financial losses due to voltage sags," in *2004 11th International Conference on Harmonics and Quality of Power (IEEE Cat. No.04EX951)*, IEEE, 2004, pp. 28–34. doi: 10.1109/ICHQP.2004.1409324.
[36] S. C. Vegunta and J. V. Milanovic, "Estimation of cost of downtime of industrial process due to voltage sags," *IEEE Transactions on Power Delivery*, vol. 26, no. 2, pp. 576–587, Apr. 2011, doi: 10.1109/TPWRD.2009.2035366.
[37] E. E. Juarez and A. Hernandez, "An analytical approach for stochastic assessment of balanced and unbalanced voltage sags in large systems," *IEEE Transactions on Power Delivery*, vol. 21, no. 3, pp. 1493–1500, Jul. 2006, doi: 10.1109/TPWRD.2005.860266.
[38] A. K. Arya, V. Gautam, and A. Kumar, "Comparative studies of stochastic techniques to minimize the cost of biomass supply networks," in *Santosh, K., et al. Recent Trends in Image Processing and Pattern Recognition. RTIP2R 2023. Communications in Computer and Information Science, vol 2027. Springer, Cham*, 2024, pp. 383–392. doi: 10.1007/978-3-031-53085-2_30.
[39] Y. S. Lim and G. Strbac, "Analytical approach to probabilistic prediction of voltage sags on transmission networks," *IEE Proceedings - Generation, Transmission and Distribution*, vol. 149, no. 1, pp. 7–14, 2002, doi: 10.1049/ip-gtd:20020008.
[40] R. Jeyagopi and V. K. Ramachandaramurthy, "Stochastic assessment of voltage sags for balanced and unbalanced faults," *International Review of Electrical Engineering (IREE)*, vol. 6, no. 5, pp. 2513–2521, 2011.
[41] Probability Methods Subcommittee, "IEEE reliability test system," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-98, no. 6, pp. 2047–2054, Nov. 1979, doi: 10.1109/TPAS.1979.319398.

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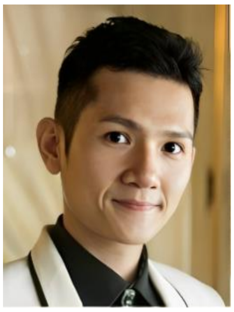

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