An Assessment of Distributed Generation Impacts on Distribution Networks using Global Performance Index

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Abstract: High levels of penetration of distributed generation (DG) are a new challenge for traditional electric power systems. Power injections from DGs change network power flows, modifying energy losses and voltage profile of the system. Proper locations of DGs in power systems are extremely important in order to obtain maximum potential benefits. This paper presents a global performance index (*GPI*) considering a wide range of technical issues for distribution networks with distributed generation. Many indices related to involvement of (DG) units in distribution system can be considered individually, but a global performance index (*GPI*) has to be obtained to give a complete comprehensive concept of the whole system. Distributed generations are extensively located and sized within a test system, where in the global performance index is computed for each configuration in order to assign the best locations of the DGs. The encouraging results are presented and discussed. [Nature and Science 2010;8(9):150-158]. (ISSN: 1545-0740).

Key Words: Distributed Generation (DG), Distribution Networks, Global Performance Index

1. Introduction

Distributed Generation (DG) can be defined as small-scale generation, which is not directly connected to the bulk transmission system and is not centrally dispatched. Generation is now being connected at distribution level, which has led to changes in the characteristics of the network [1]. Distributed generation (DG) is expected to become more important in the future generation system. They are owned by a customer, utility or another entity, and connected to the grid at a distribution voltage level [2]. Distributed resources are strategically located and operated in the system to defer or eliminate system upgrades, improve voltage profile, reduce system losses, reinforce grid, and to improve system reliability and efficiency. Recent studies have predicted that by year 2010, distributed generation will account for up to 25% of all new generation [3]. In the last few years, there has been significant contribution to research in the field of DG resource planning. Normally, DGs are integrated in the existing distribution system, and the planning studies have to be performed for optimal location and size of DGs to achieve maximum benefits. A method for solving distributed generation planning problem (location and size) in different utility scenarios as an optimization problem is proposed in Reference [4]. The objective function is based on supply-demand chain which aimed to minimize the investment and operating costs of local candidate DGs, payments toward purchasing the required extra power by the distribution company (DISCO), payments toward loss compensation services, as well as the investment cost of other chosen new facilities for different market scenarios. Reference [5] presents another method for placing DG in distribution network using rules that are often used in sitting shunt capacitors in distribution systems. A “2/3 rule” is presented to place DG on a radial feeder with uniformly distributed load, where it is suggested to install DG of approximately 2/3 capacity of the incoming generation at approximately 2/3 of the length of line. This rule is simple and easy to use, but it cannot be applied directly to a feeder with other types of load distribution, or to a networked system. References [6-7] present power flow algorithms to find the optimal size of DG at each load bus in a networked system assuming that every load bus can have a DG source. In Reference [8], the authors addressed a technique for placement of distributed generation (DG) in electric power systems using Genetic Algorithm technique keeping in view of system power loss minimization in different loading conditions. Reference [9] presents the application of a new genetic algorithm for optimal design of large distribution systems, solving the optimal sizing and location problem of feeders and substations using the corresponding fixed costs as well as the true nonlinear variable costs. It is applicable to single stage or multistage distribution designs. It indicates the application of GA for sizing and location of distributed generation. Reference [10] presents an analytical method to determine the best location of candidate DGs for minimum loss configuration. Reference [11] gives an analytical method to predict allowable DG resources on a radial distribution feeder based on harmonics limiting considerations. The authors have developed Closed-Form equations according to acceptable harmonics analysis assumptions.

2. Distribution Network Impact Indices

To quantify the effect of various indices on distributed generation planning a test system is adopted. The system and its parameters are given in Appendix.

There are various technical issues that need to be addressed when considering the presence of distributed generators in distribution systems. Ochoa et al. [12] computed several indices in order to describe the impact on the distribution system due to a presence of distributed generation during maximum power generation. D. Singh et al. [13] presents a multiobjective performance index-based size and location determination of distributed generation in distribution systems with different load models (constant, industrial, residential and commercial). References [12, 13] have attacked the DGs allocations problem partially disregarding some indices such as transformer loading and harmonics. In this paper, the overall global performance index is proposed taking into account all impact indices from DGs units. Several indices are computed and assessed in order to describe their effects on the power system operation. These indices are defined as follows:

a) Real and Reactive Power Loss Indices (ILP and ILQ):

The real and reactive power loss indices are defined as:

$$ILP = \frac{[P_{LDG}]}{[P_L]} \tag{1}$$

$$ILQ = \frac{[Q_{LDG}]}{[Q_L]} \tag{2}$$

Where, P_{LDG} and Q_{LDG} are the total real and reactive power losses of the distribution system after inclusion of DG. P_L and Q_L are the total real and reactive system losses without DG in the distribution system. The lower the values, the better the benefits in terms of loss reduction accrued to DGs locations and sizes.

b) Voltage Profile Index (IVD),at maximum load:

One of the advantages of proper location and size of the DG is the improvement in voltage profile. This index could also be used to find prohibitive locations for DGs considering pre-established voltage drop limits, and to ensure the rated voltage of each bus within the permissible limits. In this way according to equation (3), the lower the index, the better the network performance, where V1 is the root voltage (normally V1 = 100%), *"n"* is the number of nodes and V_i voltage at bus *i*. The *IVD* is defined as follows:

$$IVD = \max_{i=2}^{n}\left[\frac{|V_1|-|V_i|}{|V_1|}\right] \tag{3}$$

c) Voltage regulation index (IVR):

This index applied to ensure that the network bus voltages will not be adversely affected. The case of minimum demand during maximum power generation is also considered, since it represents a critical operating case. So, this index related to voltage regulation, shows the difference between nodal voltages during maximum and minimum demand. *IVR* values close to zero mean better voltage regulation for each bus.

$$IVR = \max_{i=2}^{n}\frac{|V_{i,L.min}|-|V_{i,L.max}|}{|V_{i,L.max}|} \tag{4}$$

where, $V_{i,\,L.min}$ is the voltage magnitude of bus *i* when that bus is loaded with the minimum demand (in this case minimum demand considered as 10% of the maximum demand), and $V_{i,\,L.max}$ is voltage magnitude of bus *i* when that bus is loaded with the maximum demand.

d) Current Capacity of Conductors (ICC):

As a consequence of supplying power near to loads, MVA flows may reduce in some sections of the network, thus releasing more capacity, but in the other sections, the MVA may also increase to levels beyond distribution networks line limits. This index gives important information about the level of MVA flows/currents through the network conductors regarding the maximum capacity of conductors. This gives the information about the need of system line upgrades. Lower values of this index indicate a more amount of available capacity. Line overloads are indicated by index values above 100%.

$$IC_C = \max_{i=1}^{ml}\left[\frac{|S_i|}{|S_{Ci}|}\right] \tag{5}$$

Where, S_i is MVA flow in line *i*, S_{Ci} is MVA capacity of line *i* and *ml* is the number of lines.

e) Transformer loading index (ICt):

This index is very important because it shows the loading ratio of each transformer regarding to the maximum capacity of transformers. Lower values of the index indicate a more amount of available capacity. Transformer overloads are indicated by index values above 100%.

$$IC_t = \max_{t=1}^{mT} \left[\frac{|S_t|}{|S_{Ct}|} \right] \tag{6}$$

Where, S_t is a transformer loading in MVA, and S_{Ct} is maximum transformer capacity in MVA and *mT* is the number of transformers.

f) Three-Phase and Single-Phase-to-Ground Short Circuit indices (ISC3 , ISC1) :

These indices are related to the protection and selectivity issues, since they evaluate the maximum short-circuit current variation between the scenarios with and without DG. The greater the values of these indices mean more contribution to the fault level, so the protection issue of the system should be re-coordinated accordingly. Low impact on this concern means close-to-unity values for *ISC3* and *ISC1* indices.

$$ISC3_i = \max_{i=1}^{n} \frac{ISC3_{i,DG}}{ISC3_i} \tag{7}$$

$$ISC1_i = \max_{i=1}^{n} \frac{ISC1_{i,DG}}{ISC1_i} \tag{8}$$

Where; $ISC3_{i,DG}$ is three-phase fault current value at bus *i* with DG, $ISC3_i$ is three-phase fault current value at bus *i* without DG, $ISC1_{i,DG}$ is single-phase-to-ground fault value at bus *i* with DG and, $ISC1_i$ is single-phase-to-ground fault current value at bus *i* without DGs and *"n"* is the number of buses.

g) Harmonic index (IH):

Among the different power quality parameters, the voltage total harmonic distortion (V.THD) is important when DGs are involved in the distribution networks. The state of the harmonic distortion is difficult to predict due to the variability and a large number of unknowns, such as detailed consumer and system characteristics. More recently, new power quality (PQ) indices have been proposed to properly express evidence the DG impact. These indices quantify the variation of PQ levels due to the DG presence [14]. DGs can reduce or improve the PQ levels. Different aspects should be taken into account in these analyses. The waveform distortion levels are influenced in a different way according to the type of DGs connection to the grid, namely, direct connection or by power electronic interfaces. In this paper, a new index that describes the voltage total harmonic distortion impact on the system in the presence of DG units is considered as:

$$IH = \sum_{i=1}^{n} \left(V_{THD_i} - V_{THD_{i,DG}} \right) \tag{9}$$

where, $V._{THD\ i}$ is a voltage total harmonic distortion of the bus *i* without adding DG units, and $V._{THD\ i,\ DG}$ is a voltage total harmonic distortion of bus *i* with adding DG units. The values of $V._{THD\ i}$ and $V._{THD\ i,\ DG}$ at the bus *i* are per unit ratios from the summation of the total harmonic distortions all over all buses, without and with adding DG units, respectively.

This index reveals the following:

- *IH* = *-Ve* distortion increases.
- *IH* = *+Ve* there is an improvement (distortion decreases).
- *IH = 0* there is no effect by DGs units.

3. The Global Performance Index.

A global performance index for the performance calculation of distribution systems for DG size and location is proposed in this work. It considers all the previously mentioned indices by strategically giving a weight for each one. This can be performed, since all impact indices are normalized (values between 0 and 1) [15].

The weighting factors are chosen based on the importance and criticality of the different loads and according to the objectives of the system operator that may be assigned from the power quality measures and components capabilities of the power system. No overarching rules can be formulated at the present time [16].

Logical and beneficially rules are thought when assigning the values of the weighting factors (*wi*) for the different operation indices. Indices that have a greater impact in improving system performance should have larger weights. For example, system that suffers from overloading on transformers or/and conductors needs higher values to be assigned for the relative indices, and so on to achieve a desired objective target.

The global performance index (*GPI*) is given by:

GPI = w1ILP + w2ILQ + w3IVD + w4IVR + w5ICc + w6ICt + w7ISC3 + w8ISC1 + w9IH. ***(10)***

Where:

$$\sum_{i=1}^{9} wi = 1.0 \wedge wi \in [0, 1].$$

These weights are intended to give the corresponding importance to each impact index for the penetration of DGs. The weighted normalized indices get their weights by translating their impacts in terms of cost. The cost may either be determined rigorously or through an engineering judgment. Regardless of the fact that one of the particular objectives may get higher satisfaction on the cost of the others, it is desirable if the total cost decreases [13].

Table 1 shows the values for the weights used in present work, considering normal operation analysis. The values are near to that given in ref. [12] after modification for the new indices proposed and added in this work. However, these values may vary according to engineer's concerns and based on the problem of a system that to be resolved.

If the system suffers from overloading on transformers or/and conductors, then, higher values are to be assigned for the corresponding indices, and so on to achieve a desired objective target. For this analysis, a current capacity of conductor ICc and transformer loading ICt indices received a significant high weights. The current capacity of conductors index ICc received weighting of (0.21) since it gives important information about the level of currents through the network regarding the maximum capacity of conductors in distribution systems. The transformer loading index ICt received weighing of (0.21) due to the impact of transformers loading. Active power losses index received weight (0.14). The behavior of voltage profile IVD receives a weight of (0.1), and IH receives weight of (0.01) due to their impacts on the power quality issue. Protection and selectivity impacts (ISC1 and ISC3) received weightings of (0.15) since they evaluate important reliability problems that DG presents in distribution networks. The global performance index function, given by equation (4.10) is minimized subject to various operational constraints to satisfy the electrical requirements for distribution network. The global performance index will numerically describe the impact of DG, considering a given location and size, on a distribution network. Close to zero values for the global performance index means higher DG benefits and leads to the best DG location.

Table 1 (weighting factors)

Indices	***Weighting factors (wi)***
ILP	*0.14*
ILQ	*0.10*
IVD	*0.10*
IVR	*0.08*
ICc	*0.21*
ICt	*0.21*
ISC3	*0.05*
ISC1	*0.10*
IH	*0.01*

4. Simulation Results And Discussions

The global performance index-based analysis is carried out on a test system extracted from reference [17] with some modifications. The single line diagram of the test system and the relevant data of its components and loads are given in Appendix. The test system consists of main substation with rated voltage 34.5KV, with total load 12.7MW. This substation (Main Bus) considered as a slack bus and connected to the distribution system via two transformers, one of them is three winding transformer. The main substation serving AC load buses with DC loads connected to DC bus (Bus11) .The system is not well-compensated and some cables and transformers are loaded above their capacities by 120%.

The impact indices presented in Section II were calculated by extensively locating and sizing DGs in the above described distribution network in order to illustrate how these indices vary regarding the insertion point and capability of a generation unit.

A. Case 1: Single DG Unit (0.9 MW, 0.85 pf lag):

The variation of impact indices and *GPI* with DG unit placed at different locations is shown in Fig. 1 and Fig. 2. The value of *IVD* and *IVR* for all the buses is near to zero. It means that bus voltage profile is improved by placement of DG.

It can be observed from Figure 1 and Figure 2 that indices *ILP, ILQ, IVD, IVR, ICc, ICt, ISC3, ISC1, IH* and *GPI* related to real power loss, reactive power loss, voltage profile, voltage regulation, line loading, transformer loading, total harmonic distortion index and the global performance index function achieve values that indicating positive impacts of DG placement in the system. It has been noticed that the *IH* index has negative values at some buses that indicated an increase in the total harmonics distortions at that bus.

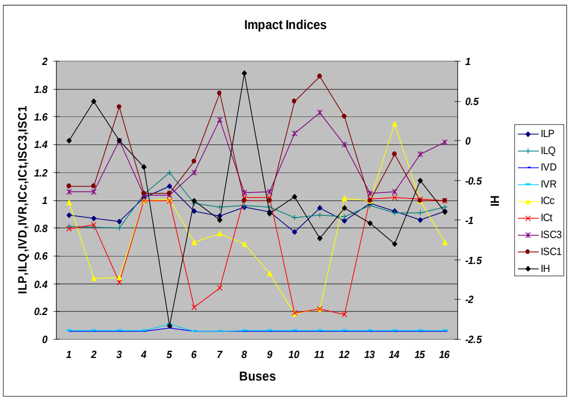

Figure1. Impact indices with a 0.9MW DG unit located at different buses in the test system.

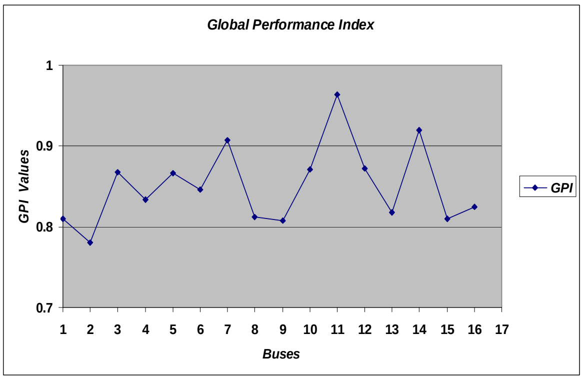

Figure 2. Global performance index (GPI) with a 0.9MW DG unit located at different buses in the test system.

Table2 Comparison between the base case and case 1

P losses (KW)	*Without DG*	*131*
	With DG	*114*
	% improving	*13%*
Q losses (KVAR)	*Without DG*	*942*
	With DG	*760*
	% improving	*19%*
Loading ratio of affected cables (LRC)	*Without DG*	*LRC of cable11 = 100 %*
	With DG	*LRC of cable11 = 44 %*
	% improving	*56%*
Loading ratio of affected transformers (LRT)	*Without DG*	*LRT of T2 = 107 %*
	With DG	*LRT of T2 = 87 %*
	% improving	*19%*
Voltage profile of affected buses (VP)	*Without DG*	*VP of Bus 3 = 93.02 %*
	With DG	*VP of Bus 3 = 96.1 %*
	% improving	*3%*

Table 3. The values of the performance indices for case 1when the DG unit has been placed at bus 2.

Performance Index	*Index Value*
ILP	*0.870*
ILQ	*0.806*
IVD	*0.056*
IVR	*0.063*
ICc	*0.440*
ICt	*0.826*
ISC3	*1.060*
ISC1	*1.100*
IH	*- 0.010*
GPI	*0.780*

Summarizing the assessment of the impact indices show that each index is capable of indicating how a DG units benefit or harms a distribution network. Therefore, the global performance index becomes essential for assessing technical impacts in a global manner regarding specific concerns of an electric utility [12]. From Fig. 2 the optimal location for DG unit is at bus 2, where the *GPI* has a minimum value.

Table 2 lists the comparative results obtained using ETAP Software for case 1. The results highlight the improvement obtained in most of the impact indices as a result of placing DG in the system. Table 3 summarizes the values of the performance indices for case 1when the DG unit is located at bus 2.

B. Case 2: Two DG,s (0.9 MW and 0.6MW, each 0.85 pf lag.):

In this case DG1 = 0.9MW should be remain at bus 2, and the same procedure has followed considering the impacts of all indices mentioned above in the previous case to get the optimal location of DG2. The variation of impact indices and the global performance index *GPI* with DG2 unit placed at different locations is shown in Fig. 3 and Fig. 4.

Fig. 4 indicates that the lower value for *GPI* index corresponds to locating DG2 at Bus 10, i. e. optimal location for DG2. Table 4 summarizes the values of the performance indices for case 2 when the DG2 unit is placed at bus 10 while, DG1 remains at bus 2. Table 5 lists the comparative results obtained using ETAP Software for case 2. The results highlight the improvement obtained in most of the impact indices as a result of placing DGs in the system.

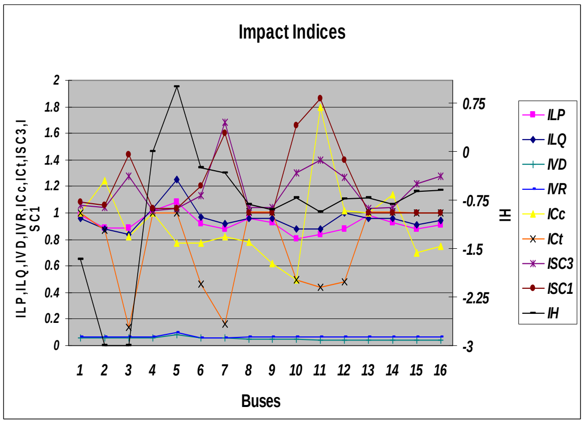

Figure 3 Impact indices with a 0.6MW DG unit located at different buses in the test system while keeping 0.9MW DGunit located at bus 2.

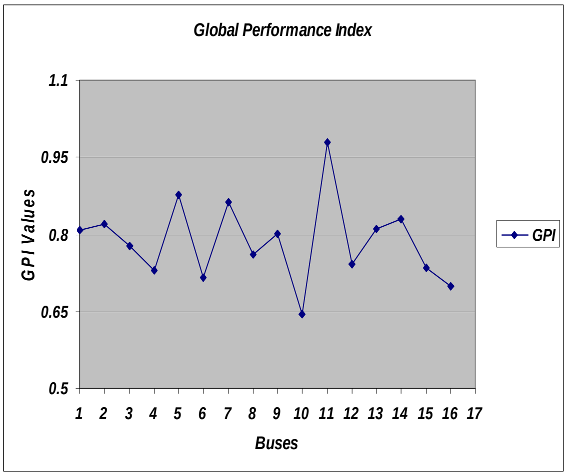

Figure 4 Global performance index (GPI) with a 0.6MW DG unit located at different buses in the test system while keeping 0.9MW DG unit located at bus 2.

Table 4 The values of the performance indices for case 2 when the DG2 unit has been placed at bus 10 while DG1 remains at bus 2.

Impact indices	*Index value*
ILP	*0.807*
ILQ	*0.880*
IVD	*0.046*
IVR	*0.064*
ICc	*0.500*
ICt	*0.500*
ISC3	*1.300*
ISC1	*1.660*
IH	*-0.710*
GPI	*0.650*

Table 5 Comparison between base case and case 2

P losses (KW)	*Without DG*	*131*
	With DG	*92*
	% improving	*30%*
Q losses (KVAR)	*Without DG*	*942*
	With DG	*672*
	% improving	*29%*
Loading ratio of affected cables (LRC)	*Without DG*	*LRC of cable4 = 121 %* *LRC of cable6 = 119 %* *LRC of cable11 = 100 %*
	With DG	*LRC of cable4 = 96%* *LRC of cable6 = 60 %* *LRC of cable11 = 44 %*
	% improving (average)	*33%*
Loading ratio of affected transformers (LRT)	*Without DG*	*LRT of T2 = 107 %* *LRT of T9 = 119 %*
	With DG	*LRT of T2 = 87 %* *LRT of T9 = 61 %*
	% improving (average)	*35%*
Voltage profile of affected buses (VP)	*Without DG*	*VP of Bus 3 = 93.02 %* *VP of Bus 11 = 94.42 %*
	With DG	*VP of Bus 3 = 96.1 %* *VP of Bus 3 = 99.03 %*
	% improving (average)	*4%*

5. Conclusions

The global performance index has been introduced in this study. A complete comprehensive concept of the whole system performance is achieved. The global performance index criterion obtained is based on the following system performance indices:

- Real and Reactive Power Loss Indices *ILP* and *ILQ*.
- Current Capacity of Conductors *ICC* and Transformer Loading Index *ICt* which are related to the system MVA capacity enhancement.
- Voltage Profile Index *IVD*, Voltage Regulation Index *IVR* and Harmonic Index *IH* which are related to the power quality issue.
- Three-Phase and Single-Phase-to-Ground Short Circuit Indices *ISC3*, *ISC1*. These indices are related to the protection and selectivity issues.

The developed technique introduces a more precise appraisal of the global performance index *GPI* based on several operating indices that assign the optimum location of the DGs in the power system. Weighting factors for the different individual indices are assigned to reflect the degree of importance of the relative index in improving the critically operating issues of the system. The proposed Weighting factors are flexible since electric utilities have different concerns about losses, voltages, protection schemes, etc. This flexibility makes the proposed methodology even more suitable as a tool for finding the most beneficial places where DGs may be located, as viewed from an electric utility technical perspective. Consequently, these may have an economic influence, since technical impacts may be used to shape the nature of the contract that might be established between the utility and the DG owner.

6. References

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Appendix

Figure 1 shows the 17-Bus test system under study. Tables 1-3 show the data of the test system components

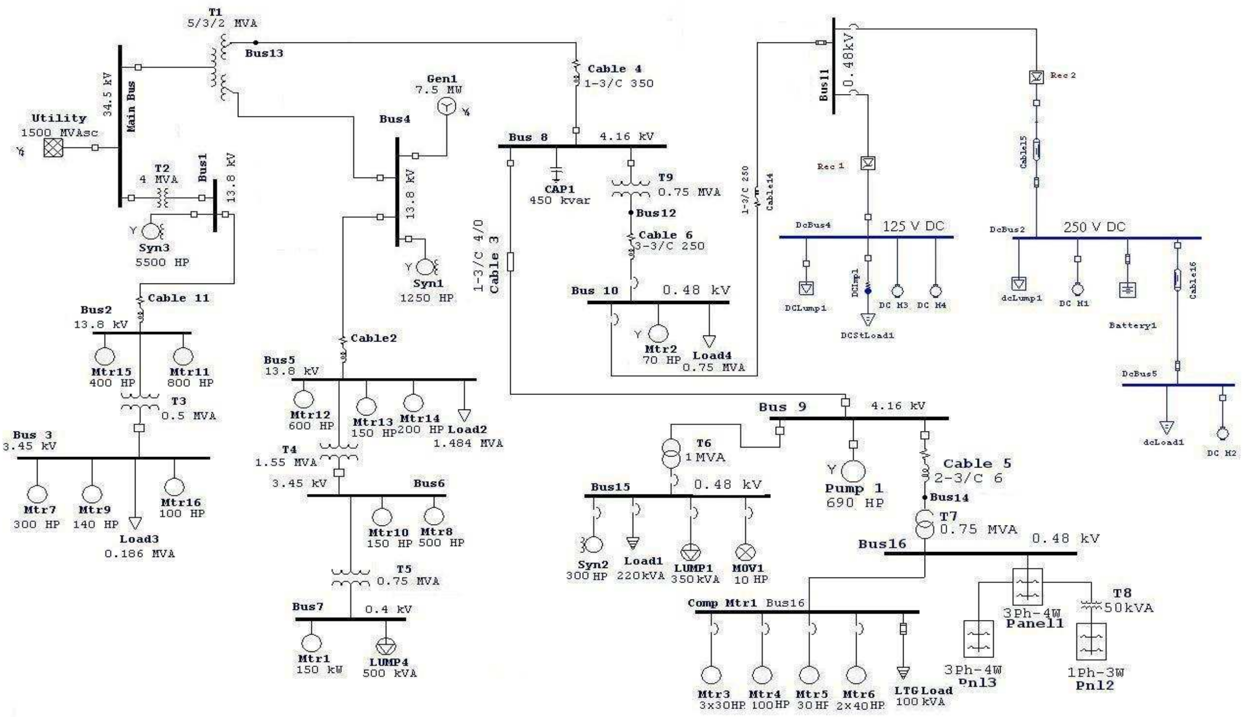

Table 1: Cable impedances in ohm

Cable ID	*R (Ω / 1000 m)*	*X (Ω / 1000 m)*
2	0.65696	0.34112
3	0.21320	0.14629
4	0.21320	0.12514
5	1.67280	0.20008
6	0.18106	0.12431
11	1.67280	0.17417
14	0.18106	0.12431

Table 2: Transformers Data

Trafo. ID	*MVA*	*%Z*		*X/R*
T2	5.750	7.000		12.9
T3	0.700	5.500		5.8
T4	1.550	5.500		5.8
T5	0.750	5.750		5.8
T6	1.000	5.750		5.8
T7	0.750	5.750		5.8
T9	0.750	5.750		5.8
T1	6.000	Zps	6.5000	13
	3.000	Zpt	6.5000	14
	3.000	Zst	11.000	15

Note : T1 is three winding transformer.

Table 3: Load Data

Bus No.	Motor Load		Static Load	
	MW	***MVAR***		***MW***
1	*4.353*	*1.712*	*0000*	*0000*
2	*0.959*	*0.403*	*0000*	*0000*
3	*0.456*	*0.197*	*0.171*	*0.073*
4	*0.997*	*0.410*	*0000*	*0000*
5	*0.786*	*0.364*	*1.250*	*0.800*
6	*0.531*	*0.227*	*0000*	*0000*
7	*0.463*	*0.257*	*0.128*	*0.079*
8	*0000*	*0000*	*0000*	*-0.450*
9	*0.551*	*0.232*	*0000*	*0000*
10	*0.065*	*0.029*	*0.749*	*0.001*
11	*0.166*	*0.049*	*0000*	*0000*
12	*0000*	*0000*	*0000*	*0000*
13	*0000*	*0000*	*0000*	*0000*
14	*0000*	*0000*	*0000*	*0000*
15	*0.457*	*0.225*	*0.295*	*0.156*
16	*0.283*	*0.134*	*0.179*	*0000*