Optimal Allocation of Dispersed Generators, Capacitors and Distributed Energy Storage Systems in Distribution Networks

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Abstract—**The paper deals with the optimal sizing and allocation of dispersed generation, distributed storage systems and capacitor banks. The optimization aims at minimizing the sum of the costs sustained by the distributor for the power losses, for network upgrading, for carrying out the reactive power service and the costs of storage and capacitor installation, over a planning period of several years. A hybrid procedure based on a genetic algorithm and a sequential quadratic programming-based algorithm was used. A numerical application on a 18-busbar MV balanced 3-phase network was performed in order to show the feasibility of the proposed procedure.**

Keywords- Dispersed storage and generation, Electrical distribution system planning, Genetic Algorithms.

I. Introduction

The deregulation of electricity generation and retailing introduces new paradigms to the planners and operators of electrical distribution systems. Special attention is required when dealing with ancillary services, such as the reactive power service, which are essential for the operation of the network, but can cause operators to incur not readily identifiable costs in their provision. On the other hand, this problem has becoming of growing interest and complexity, due to the widespread presence in distribution systems of Dispersed Generation (DG) and Distributed Energy Storage Systems (DESSs) [1,2].

DG has the potential to provide technical and economic benefits to the distribution system, such as the reduction of power losses and/or deferment of investments for network enforcing, as well as power quality improvement, and it is an option that distribution planners should explore in their search for the best solution to electric supply problems. On the other hand, it should be recognized that, whether the DG is misused or misplaced, it may easily cause degradation of power quality, reliability, and control of the system or it may increase losses and affect voltage regulation.

The application of DESSs can be considered in order to aid the optimal integration of DGs as well as to avoid the costs related to the expansion of distribution networks. In particular, the energy storage systems can be used to reduce the variability of some DG sources, to counter the voltage rise effect or to improve the power quality in distribution networks. Moreover, an optimal control of DESSs allows the operators of electrical distribution systems to improve the reactive control and, as a consequence, to reduce the overall costs [3-6].

Considering an active distribution system, this paper deals with the optimal allocation (both size and location) of DG units, DESSs and capacitors. The objective is to minimize the sum of the costs sustained by the distribution network owner for the power losses, the network upgrading, for carrying out the reactive power service and for DESS and capacitor installation, over a period of study of several years. The results of the optimization problem consist in obtaining not only the optimal allocation of DGs, DESSs and capacitors, but also the optimal charge/discharge cycles of DESSs and the scheduled reactive powers that DGs, DESSs and capacitors have to provide with the common objective of total costs minimization.

This optimization problem is a mixed integer, non-linear, constrained optimization problem in which a cost objective function has to be minimized while meeting a number of equality constraints (e.g., power flow equations) and inequality constraints (e.g., admissible ranges of the bus voltages and storage energy constraints).

One of the algorithm most frequently used to solve similar problems is the Genetic Algorithm (GA) that has been shown to be capable of finding good solutions, although it can require very high computational efforts, mainly in solving planning problems that require to take into account a large time horizon.

In order to contain the computational efforts, this paper proposes a hybrid algorithm. In fact, the planning problem is faced by means of a procedure that consists of a GA able to generate a set of possible location and sizing of DGs, DESSs and capacitor banks and an inner Optimal Power Flow (OPF) based on Sequential Quadratic Programming (SQP) used to obtain the optimal daily charge/discharge cycles of DESSs and the scheduled reactive power that DGs, DESSs and capacitors have to provide.

The paper is organized as follows. In Section II, the planning problem is formulated and the solving procedure is described. Then, the planning problem is solved with reference to a 18-busbar MV balanced 3-phase network and the results are discussed in Section III.

II. The Optimal Planning Problem

Let us consider a n nodes MV radial distribution network where DGs, DESSs and capacitor banks have to be located and sized. The loads are characterized with some assigned typical daily load variations that are assumed to grow in the planning time horizon.

The proposed procedure aims at finding not only the optimal size and location of DGs, DESSs and capacitor banks but also the daily charge/discharge cycles of DESSs and the scheduled reactive power that DGs, DESSs and capacitors have to provide. Due to the system characteristics, also the network upgrading is considered among the planning alternatives.

The procedure consists in the minimization of the total costs sustained by the distribution network owner (cost of power losses, cost of network upgrading, cost of reactive power and costs of DESS and capacitor installation [1]) while meeting proper equality and inequality constraints, i.e.:

$$\text{Min}\, f_{obj}(\boldsymbol{X},\boldsymbol{C}) \tag{1}$$

subject to:

$$\psi(\boldsymbol{X},\boldsymbol{C})=0 \tag{2}$$

$$\eta(\boldsymbol{X},\boldsymbol{C}) \le 0, \tag{3}$$

where: $\boldsymbol{X}$ is the system state vector (voltage at all system busbars) and $\boldsymbol{C}$ is the control vector, related to the DESSs charge/discharge profile, reactive power provided by DESSs, DGs and that imported by HV, the allocation nodes of DESSs, DGs and capacitors as well as their sizes.

We note that the objective function (1) includes the reactive costs since in a deregulated power system, customers are expected to pay for the reactive power support service based on some pricing structure [8-11], so the planning of reactive power devices, taking into account all the involved economic aspects of the reactive power, becomes of great interest to a distribution company.

The equality constraints to be met include power flow equations and daily DESSs energy balance.

The inequality constraints to be met include voltage admissible ranges and limits on devices rating.

The optimization problem (1)-(3) is a mixed variables problem that involves both continuous (e.g., DESS charge/discharge profile, DESS and DG reactive power) and discrete (e.g., device sizes, allocation nodes) variables that can be solved with a GA. Since GAs can require very high computational efforts, this paper proposes a mixed algorithm including both GA and inner OPF: GA is used for generating populations characterized by sizes and locations of DESSs, DGs and capacitors, while the inner OPF is used for obtaining an optimal daily charge/discharge cycles of DESSs and the scheduled reactive power that DGs, DESSs and capacitors have to provide.

In particular (Fig. 1), the GA creates an initial population whose individuals are characterized by the following variables: allocation nodes of DGs, DESSs and capacitors, number of elements of a pre-assigned size of DGs, DESSs and capacitors. In fact, DGs, DESSs and capacitors are assumed to be integer multiples of an unit base; for example, in the case of capacitors and assuming the base unit equal to CU kVar, the corresponding control vector elements at each bus can assume the values [0, CU, 2CU, 3CU, etc.].

Once generated the initial population, the SQP based algorithm performs an optimization aimed at finding the optimal daily charge/discharge cycles of DESSs and the scheduled reactive powers that DGs, DESSs and capacitors have to provide while minimizing the losses and voltage regulation costs on the whole planning period. Note that, since capacitor bank reactive powers treated as continuous variables, in spite of their discrete nature, a discretization is needed; the procedure proposed in [12] can be used for.

The results of the SQP based optimization are the inputs of the next genetic algorithm step that consists in the fitness function calculation and in the subsequent generation of the next population until the stopping criterion is reached.

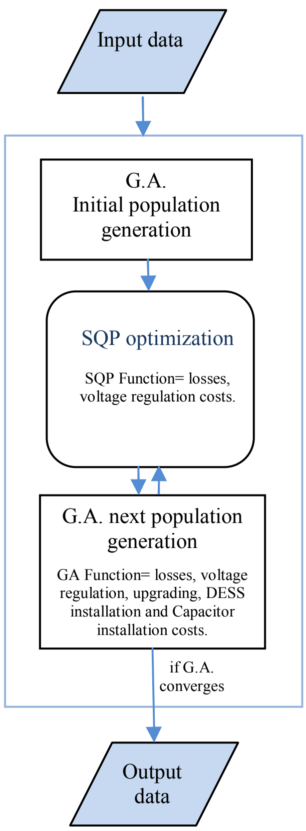

Figure 1. Flowchart of the proposed procedure

In the following more details of both the GA and SQP based algorithms are given.

[1] In our paper DGs are assumed to be owned by independent power producers, as it happens in most European countries

A. Genetic algorithm fitness function

The GA fitness function includes all the costs sustained by the distribution network owner over the whole planning period. More in detail the fitness function is:

$$F_{GA} = \left(C_{LOSS} + C_{DG} + C_{HV} + C_{CAP} + C_{DESS} + C_{UP}\right) \quad (4)$$

where:

$$C_{LOSS} = \Pr_L \sum_{i=1}^{N_Y} \left[\left(\frac{1+\alpha_L}{1+a} \right)^{i-1} \sum_{k=1}^{N_{L,i}} \left(N_{days,k} \, P_{L,i,k} \Delta T_{i,k} \right) \right]$$

$$C_{HV} = \Pr_{HV} \sum_{i=1}^{N_Y} \left[\left(\frac{1+\alpha_{HV}}{1+a} \right)^{i-1} \sum_{k=1}^{N_{L,i}} \left(N_{days,k} \, Q_{HV,i,k} \Delta T_{i,k} \right) \right]$$

$$C_{DG} = \Pr_{DG} \sum_{i=1}^{N_Y} \left[\left(\frac{1+\alpha_{DG}}{1+a} \right)^{i-1} \sum_{k=1}^{N_{L,i}} \left(N_{days,k} \, Q_{DG,i,k} \Delta T_{i,k} \right) \right]$$

$$C_{CAP} = \Pr_{CAP} \sum_{j=1}^{n_{CAP}} \left(m_{CAP,j} \cdot Q_{CAP\_base} \right)$$

$$C_{DESS} = \Pr_{DESS} \sum_{j=1}^{n_{DESS}} \left(m_{DESS,j} \cdot P_{DESS\_base} \right)$$

where N_Y is the number of years of the planning period with each year i characterized by daily load variations that are discretized by $N_{L,i}$ time intervals of duration $\Delta T_{i,k}$; $N_{days,k}$ is the number of days characterized by load level k; $\Pr_{HV}$ is the HV reactive power price, $\Pr_L$ is the losses unitary cost, $\Pr_{DG}$ is the DG reactive power price, P_{DESS_base} and $\Pr_{DESS}$ are the DESS unitary size and their installation price, Q_{CAP_base} and $\Pr_{CAP}$ are the capacitor bank unitary sizes and their installation prices, $m_{DESS,j}$ and $m_{cap,j}$ are the number of the base units of pre-assigned size of DESSs and capacitors allocated at node j; with reference to the i^{th} year and at k^{th} system state: $P_{L,i,k}$ represents the distribution system's active power losses; $Q_{DG,i,k}$ is the DG total reactive power; $Q_{HV,i,k}$ is the reactive power imported from the HV grid; $\alpha_L, \alpha_{DG}, \alpha_{HV}$ are the rates of change in unit cost of the active power and DG and HV imported reactive powers, respectively; a is the assumed discount rate.

We note that in (4) the cost of the reactive power imported from the HV grid is included since, as shown in [7], in a competitive market, the Transmission Network Operator will assign a cost for the reactive power injected into distribution networks.

The upgrading costs are the cost of every branch including the construction, residual management and losses costs over the whole planning period. The annual increase of load demand as well as the generation units connected to distribution systems lead to the increase of line current flows. When the current flows exceed the line limits, the upgrading of that line including corresponding costs are required. Further details on the upgrading cost evaluation and features can be found in [6].

B. SQP based optimization

As previously evidenced, the SQP method based algorithm is used for obtaining the optimal daily charge/discharge cycles of DESSs and the scheduled reactive power that DGs, DESSs and capacitors have to provide.

The objective function to be minimized is the costs sustained by the distributor that are linked to the reactive power service and to the power losses.

Referring to the planning period of N_Y years, the objective function to be minimized is given by:

$$F_{obj} = \left(C_{LOSS} + C_{DG} + C_{HV}\right), \quad (5)$$

with symbol meanings already defined in (4).

As for the *equality constraints* to be satisfied, the typical power flow equations are properly formulated to take into account the problem variables. In this regard, the reactive powers produced by the DGs, and the capacitor banks as well as the DESS active and reactive powers are control variables, so they are included in the power flow balance equations. Equality constraints are also included with reference to the energy stored in the DESS that at the beginning and at the end of each day must have an assigned fixed value. The energy stored can be evaluated with reference to each day as [2][2]:

$$E_{DESS,j,k} = E_{DESS,j,k\text{-}1} - P_{DESS,j,k} \Delta T_k \, , \quad (6)$$

where $E_{DESS,j,k}$ is the energy stored in the DESS located at node j at the end of the k^{th} time interval[3] that has to be the same at beginning and at the end of each day and is limited by the size of the storage device, $P_{DESS,j,k}$ is the power furnished by the DESS located at the j^{th} node in the time interval ΔT_k.

Inequality constraints involve the maximum allowable energy stored that is linked to the DESS size and charge time [8,10] and constraints related to the voltage and power limits. In particular:

- voltage at all the busbars load have to fall into the range [V_{min}-V_{max}] p.u.;
- DESS active powers, DG and capacitor reactive powers have to fall into an admissible range;
- DESS and DG active and reactive powers are also limited by the interfacing converter sizes;
- DESS stored energy have to fall into an admissible range.

As far as the reactive power of capacitors, it should be noted once again that, in the SQP based algorithm, it is treated as a continuous variable despite of its discrete nature, thus the heuristic procedure proposed in [12] has been used for assigning the permitted discrete variable values.

III. Application

The planning problem formulated in the previous section was solved with reference to the 18-busbar MV balanced 3-phase network [13] shown in Fig. 2.

[2] In the following the subscript i is neglected since the equations are referred to each single year. Moreover, for sake of clarity the equation refers to a unique daily load profile per year.

[3] For the sake of simplicity, the efficiency of the storage process has been neglected.

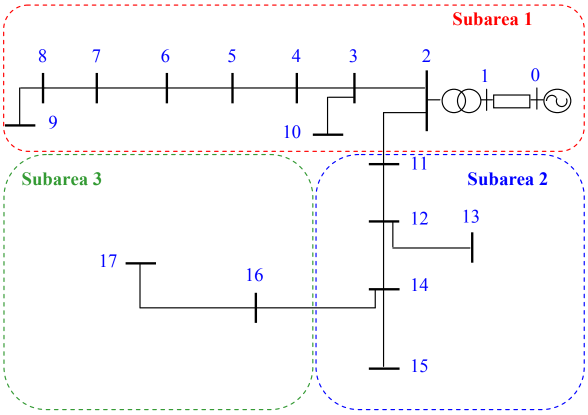

Figure 2. Distribution network scheme.

The test system data are reported in Appendix A along with the load base values. The MV network is supposed connected to a HV network through a 138/12.5 kV, 18 MVA transformer having v_{cc}%=7%. A constant value of 1.05 p.u. was fixed for the voltage at the node #2 in all the simulations.

For the sake of simplicity, in the numerical applications we optimized the siting and sizing of no more than two capacitor banks, two DGs and two DESSs. All the MV network nodes are candidate locations for capacitor banks, DGs and DESSs.

For the capacitors, fixed banks of 450 kVAr were considered.

Concerning the DG, wind generation units have been considered, that, in particular, can have two possible configurations: the first is with a 500 kW Wind Turbine (WT) connected to the grid through a 600 kVA static converter and the second is with a 1000 kW WT connected to the grid through a 1200 kVA static converter. The active power produced by each generator depends on both the WT features and wind speed on the area where it is installed. In particular, three different areas of candidate nodes were considered with different forecasted wind speed (subarea 1, subarea 2 and subarea 3 in Fig. 2). The wind speed in the subareas is generally characterized by a proper probability density function. However, in this paper, without loss of generality, a constant wind speed and equal to its mean value on each time interval is assumed. The corresponding WT power production is evaluated by means of the typical relationship between wind speed and WT power.

Two DESS units were allocated, each one characterized by 1 or 2 REDOX battery units of 500 kW connected to the grid through 600/1200 kVA static converter.

As far as the costs are concerned, we referred to [8,12].

The period taken into consideration for the planning study was 20 years. All the costs were assumed to have a yearly rate of increase of 2% with a discount rate of 5% for the present value calculation. A four-step function was used to approximate a daily load curve for all the network nodes (Fig. 3). Eventually, increments of the power demand were considered starting from the 75 % of the base value (Tab. III) up to a value of 100% in the last year.

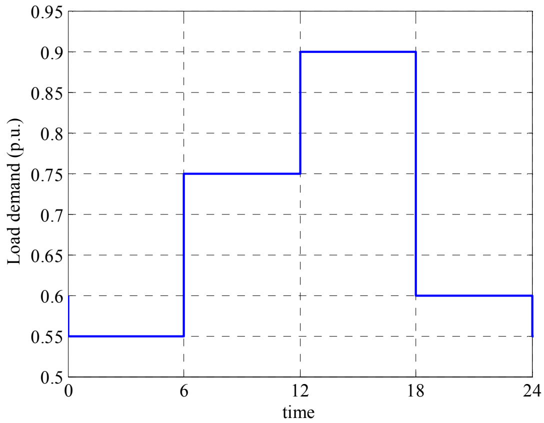

Figure 3. Daily load demand variation curve.

Concerning the GA implementation, the stopping criterion was based on the control of the fitness function improvements. Moreover, a maximum number of generations was also fixed.

In the following some results of the application are reported. Table I shows the allocation nodes for DGs, DESSs and capacitors as well as the number of DESS and DG base units located at each node.

TABLE I. OPTIMAL ALLOCATION AND SIZES OF DGS, DESSS AND CAPACITORS

DESS		DG		Capacitor
node	*Rating*	*node*	*Rating*	*node*
6	1×500kW	9	1×1000kW	3
14	1×500kW	16	1×1000kW	16

Figs. 4-9 report some results of the SQP based optimization for the typical daily load profile of the last year.

In particular, Figs. 4 and 5 show the charge/discharge profile and the reactive power of the DESS located at node #6, respectively. The apparent power of the DESS is equal to the maximum value (600 kVA) in each time interval.

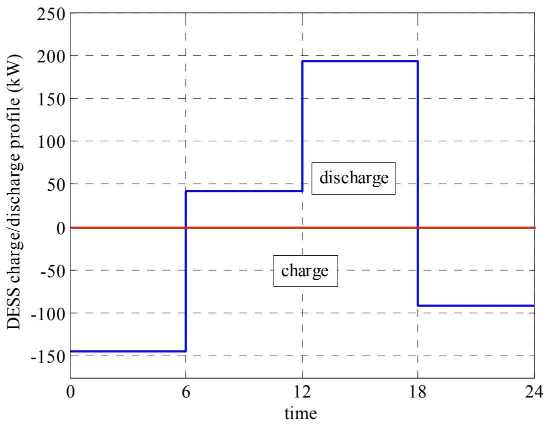

Figure 4. Daily charge/discharge profile of DESS at node #6.

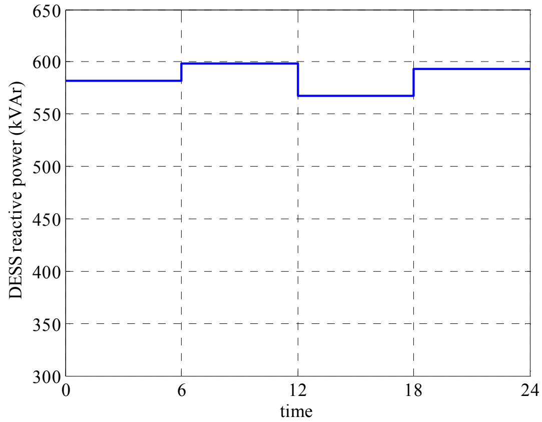

Figure 5. Reactive power furnished by the DESS at node #6.

Figs. 6-8 show the active, reactive and apparent power of the DG located at node #9, respectively. Note that, the active power produced by the DG is an input value depending on the allocation site, whereas the reactive power is an optmization variable.

Eventually, Fig. 9 shows the reactive power imported from the HV network at each time interval.

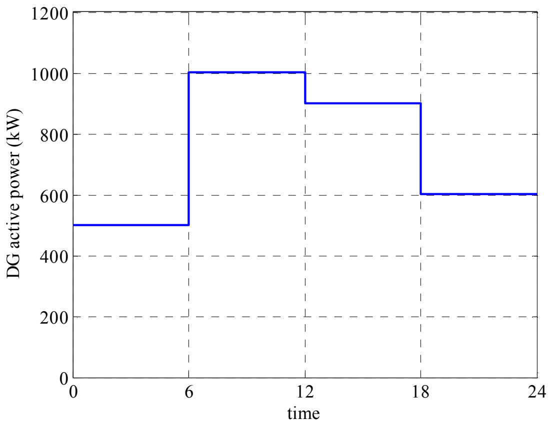

Figure 6. Active power furnished by the DG at node #9.

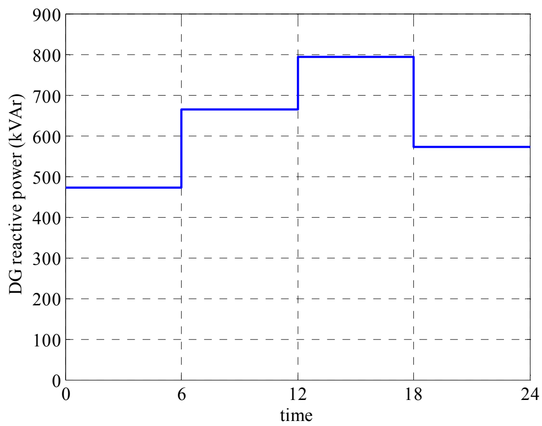

Figure 7. Rective power furnished by the DG at node #9.

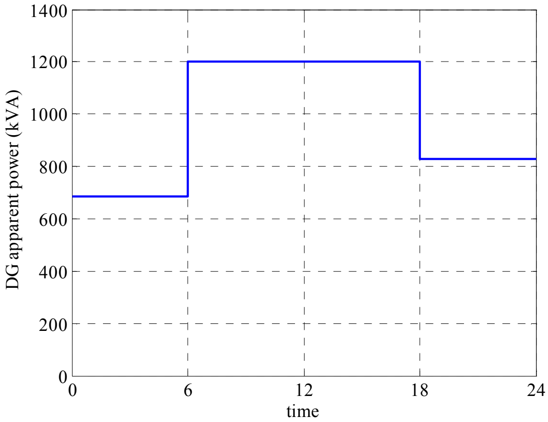

Figure 8. Apparent power furnished by the DG at node #9.

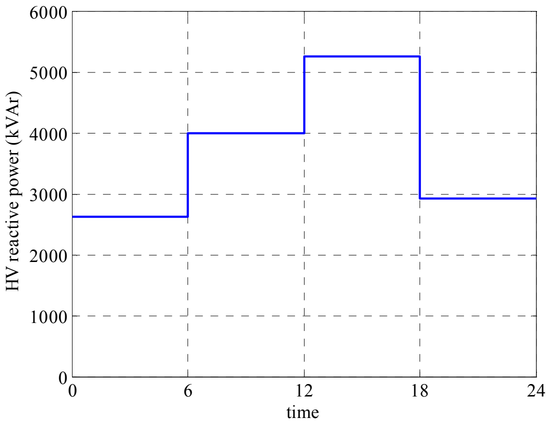

Figure 9. Reactive power imported by HV Network.

The comparison of Figs. 4 and 5 puts in evidence, as expected, the contribution of DESS to the reactive power provision, which is limited by the converter size. As shown in the charge/discharge profile (Fig. 4), the charging stage is operated during the low loads demand. Moreover, it is worth nothing that, even if the use of DESS evidences economical and technical advantages, on the other hand, an excessive oversizing of storage can have a detrimental effect on the network operation by increasing the losses; in fact, in each node only 1 device (Tab. I) is located.

Fig. 7 puts in evidence the contribution of DGs to the reactive service; the reactive power furnished by the DG is limited by the converter size (Fig. 8), and by the need of minimizing the total costs sustained by the distribution network owner.

IV. Conclusions

A mixed SQP based method and GA procedure for the optimal allocation and sizing of DGs, DESSs and capacitors in distribution networks is proposed. The GA determines the populations constituted by a set of candidate nodes where to locate the devices along with their sizes. The SQP optimizes the charge/discharge cycles of DESSs and the scheduled reactive powers that DGs, DESSs and capacitors have to provide with the common objective of total costs minimization. The procedure has been implemented on a 18-busbar MV balanced 3-phase network and the results have confirmed its feasibility. Future researches will consider more complex distribution systems and propose further improvements to reduce the computational efforts.

APPENDIX A

TABLE II. TETS SYSTEM DATA [13]

Line		R (p.u.)	X_L (p.u.)	X_C (p.u.)
0	1	0.00050	0.00354	0
1	2	0.00031	0.06753	0
2	3	0.00431	0.01204	0.000035
3	4	0.00601	0.01677	0.000049
4	5	0.00316	0.00882	0.000026
5	6	0.00896	0.02502	0.000073
6	7	0.00295	0.00824	0.000024
7	8	0.01720	0.02120	0.000046
8	9	0.04070	0.03053	0.000051
3	10	0.01706	0.02209	0.000043
2	11	0.02910	0.03768	0.000074
11	12	0.02222	0.02877	0.000056
12	13	0.04803	0.06218	0.000122
12	14	0.03985	0.05160	0.000101
14	15	0.02910	0.03768	0.000074
14	16	0.03727	0.04593	0.000100
16	17	0.02208	0.02720	0.000059

TABLE III. LOAD BASE VALUES (P_{BASE}=10 MVA)

Node	P_c (p.u.)	Q_c (p.u.)
1	0	0
2	0	0
3	0.03	0.018
4	0.05	0.03
5	0.16	0.1
6	0.31	0.233
7	0.09	0.06
8	0.03	0.018
9	0.11	0.068
10	0.06	0.037
11	0.11	0.068
12	0.04	0.025
13	0.03	0.018
14	0.09	0.06
15	0.06	0.037
16	0.11	0.068
17	0.03	0.018

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