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Load Forecast Based ORPF For Minimum Energy Loss

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Abstract

An efficient and practical method for minimization of energy loss in electrical networks over intervals of time is presented. The proposed method uses different loading conditions during each given time interval instead of single snapshot loading of the network. The given interval is divided into several subintervals. The first load condition is a current snapshot and subsequent ones are forecasted. Energy loss minimization and power loss minimization are compared by simulated application to the IEEE 6-bus system. As seen in these simulation results, the proposed method not only improves the voltages profile, but it also decreases the total energy loss over the given time interval.

Keywords: (ORPF) Optimal reactive power flow, (PLM) power loss minimization, (ELM) energy loss minimization.

تقليل مفاقيد الطاقة باستخدام التنبؤ بالحمل كأساس في (ORPF)

الخلاصة

قدمت في هذا البحث طريقة كفوءة وعملية لتقليل مفاقيد الطاقة في الشبكات الكهربائية لفترة زمنية محددة. هذه الفترة الزمنية تم تقسيمها إلى فترات ثانوية (اعتمادا على حجم التغيرات المتوقعة في الحمل)، وتم اخذ حالات مختلفة للحمل في الشبكة، الحالة الأولى تمثل صورة الحمل في بداية الفترة (الحمل الحالي للشبكة) أما الحالات التالية فإنها تمثل الحالات المتنبأ فيها للحمل في بداية كل فترة ثانوية. تم مقارنة هذه الطريقة (تقليل مفاقيد الطاقة) مع طريقة تقليل مفاقيد القدرة التي تأخذ فقط حالة الحمل الحالية بواسطة تطبيق المحاكاة بالحاسوب على منظومة " IEEE 6-bus"، ومما تم ملاحظته من النتائج إن الطريقة المقترحة لم تحسن منسوب الفولتية فحسب وإنما إضافة لذلك قللت مفاقيد الطاقة الكلية خلال الفترة الزمنية المحددة.

List of Symbols

E_L : total energy loss.
$g(i,j)$: the conductance from bus i to j.
k : kth period.
n : number of periods.
N : number of buses.
P_L : total power loss in the transmission system.
P_L^k : power loss in the kth period
Q_C: VAR generation of shunt capacitors.
Q_G^k :VAR generation of generators.
Q_L: VAR generation of shunt inductors.
ΔP^k : active power mismatch at all buses.
ΔQ^k : reactive power mismatch at all
T : transformer tap settings.
t^k : the duration of kth period

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V_G^k : voltage magnitudes at generator buses.

$V_i\angle\delta_i$: voltage at bus i.

$V_j\angle\delta_j$: voltage at bus j .

V_l^k : voltage magnitudes at load buses.

$V^{\max}$: maximum value of bus voltage.

$V^{\min}$: minimum value of bus voltage.

1. Introduction

Optimal power flow (OPF) is one of the major issues in the operation of power system and has attracted a lot of attention since 1962 [1]-[8]. This problem can be divided into two sub-problems, real power optimization problem (MW dispatch) and reactive power optimization problem (MVAR dispatch)[1]. The main objective of the first problem is to minimize the system fuel cost, and for the second problem is to minimize the system power losses and improve voltage profiles. For both optimization sub-problems should be maintain an acceptable system performance in terms of limits on generator real and reactive outputs, transformers tap settings and bus voltages levels[2]. In many cases, the optimal reactive power flow (ORPF) is considered independently [3], and in some others it is combined with MW dispatch[4]. However, in most real-time applications, these two sub-problems have been assumed decoupled and thus treated independently.

The main objectives of the ORPF problem are[5]:

i)To keep the network voltage profile in an acceptable range $(V^{\min} \leq V \leq V^{\max})$.

ii)To minimize the total transmission power loss of the network.

iii)To avoid excessive adjustment of the system configuration ,i.e. to minimize transformer tap setting changes and the switching operations of discrete VAR sources.

Many studies dealt with optimizing the reactive power dispatch with no consideration of the third objective , i.e. transformer taps and switching of VAR sources .

Only few papers have addressed the on-line application of optimal reactive power flow (ORPF) [6,7] including the minimization of the total power loss as objective function. In the on-line application of ORPF, different objective functions can be minimized. These objective functions include minimization of total power loss, and minimum number of control shifts (number of control variables which should be changed is minimized) for removing constraints violations in load bus voltages and generators reactive power.

The method mentioned in reference [6] is to minimize the total power loss exclusively on the basis of load forecast, while in reference [7] the power loss is minimized on the basis of real time load conditions without considering the load forecast during the next hour. In this work, the total energy losses is minimized on the basis of the data on-line and the load forecast during the next intervals (hours). This method uses discrete and continuous controls at the start of the hour, then running ORPF program for removing any voltage violations every period (several minutes) employing only continuous controls(generator voltages) and keeping the discrete controls (transformer tap settings and switching of VAR sources) constant during that interval at settings that are optimal over the entire hour.

Many optimization methods have been applied in solving ORPF problems, such as gradient searching method, Newton method, interior-point method and sequential linear/quadratic programming method…etc. In recent years, some new optimization methods, such as simulated annealing method, fuzzy logic, artificial neural network method and genetic algorithm are applied to solve the OPF problem[8].

2. Problem Formulation

Before stating the formulation of the problem, the selection of interval duration and the strategy of control variable settings should be explained. The on-line load profile and the load forecast for the upcoming hours are inspected. Depending on the size of load variations and the experience of the operator, an interval varying from one to several hours may be selected. Each interval is divided into "*n*" periods. The number and duration of periods depends on the anticipated load profile changes.

Figure(1), explains how to select the intervals and periods for daily load curve. Two time intervals, between 1 A.M to 5 A.M and 5 A.M to 7 A.M are selected. Each interval is divided into several periods. The interval between 1 A.M to 5 A.M is divided into three periods, due to small load changes in this interval. During 5 A.M to 7 A.M, due to rapid changes in load, four periods are selected . In this work intervals are taken as one hour and the period in each interval is set at 15 minutes up to 30 minutes.

In the setting procedure all the control variables (continuous and discrete) are set at the beginning of each interval. At the beginning of periods (2,3,…,*n*) only the continuous control variables may be adjusted.

The formulation of the problem is explained in two sections. In the first , the loss minimization problem is formulated on minimizing the active power loss in the whole system .In the second section, the problem formulation based on the total energy loss minimization for the next coming hour is addressed.

2.2.1 Active Power Loss Based Problem Formulation

It is assumed that the optimal MW dispatch is already dominated by economic objectives before the MVAR dispatch is considered and the active power generation of all the generators except at the slack bus are constants. The objective function is to minimize the system total power loss. The control variables include generator voltages, transformer tap settings and reactive power generation of VAR sources (capacitive or inductive). The constraints of this problem are voltage limits on the load buses, ,VAR/voltage limits of the generators, tap setting limits, and VAR source limits[5]. This objective function is given by:

Minimize

$$P_L = \frac{1}{2}\sum_{i=1}^{N}\sum_{\substack{j=1 \\ j\neq i}}^{N} g(i,j)[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)] \qquad (1)$$

The constraints of this problem are formulated as follows:

(a) Continuous-variables constraints

$$\left.\begin{aligned} V_l^{\min} &\le V_l^k \le V_l^{\max} \\ V_G^{\min} &\le V_G^k \le V_G^{\max} \\ Q_G^{\min} &\le Q_G^k \le Q_G^{\max} \end{aligned}\right\} \qquad (2)$$

for k=1,2,…,n

(b) Discrete-variables constraints

$$\left.\begin{array}{l} Q_C^{\min} \le Q_C \le Q_C^{\max} \\ Q_L^{\min} \le Q_L \le Q_L^{\max} \\ T^{\min} \le T \le T^{\max} \end{array}\right\} (3)$$

(c) Power flow equality constraints

$$\left.\begin{array}{l} \Delta P^k = 0 \\ \Delta Q^k = 0 \end{array}\right\} \text{ for k=1,2,...,n (4)}$$

where the index (k) denotes values that are adjusted at each period. The discrete control variables Q_C, Q_L and T are kept constant during the hour, to minimize equipment wear, for this reason they are not designated with the index (k).

This problem can be solved by the ORPF program which should be run at the beginning of every hour to optimize reactive power flow and find the optimal settings of all the controls. Then, reruns for (2, 3,...n) periods in the interval with only the continuous controls to be adjusted.

2.2.2 Energy Loss Based Problem Formulation

In the formulation of the energy loss minimization problem the total power loss (equation1) is replaced by the total energy loss over a given interval. For this calculation, it is assumed that the bus loads remain constant during each n period. The bus voltages during each period are also constant, but differ from one period to the next. Therefore, energy minimization method is based on minimizing summation of power loss in all n periods of each hour and the objective function can be formulated as:

$$\min E_L = \sum_{k=1}^{n} P_L^k . \ t^k \quad (5)$$

where E_L is the total energy loss for one hour and P_L^k is the power loss in the kth period which can be calculated from equation (1) with the value of voltage for period k and t^k is the duration of *kth* period. The constraints of the problem here are similar to the constraints which were given in equations (2)-(4) for power loss minimization (PLM) problem.

This problem can also be solved by the ORPF program. This problem is solved at the beginning of each interval for the minimization of energy loss. Discrete and continuous controls are set at the beginning of the hour from the results of the ELM run. The continuous control variables are set at each n period by the ORPF for removing the violations of bus voltages constraints or for power loss minimization if violations do not exist. The main steps of the proposed method are shown in the Fig.2. It should be noted that PLM method here is different from ELM method in step 2, i.e., at the beginning of each interval PLM minimizes the power loss of period 1 only by using all control variables.

3. Frequency of Running the ORPF

An important aspect in running the ORPF program is the frequency of its execution. This frequency can be varied from once every several minutes to once every several hours .The frequency depends on some important factors, such as load profile, constraint violations ,and the importance of power loss reduction and/or maintaining an appropriate voltage profile[5]. For finding the appropriate frequency of running the ORPF ,the daily load profile of Fig.1 should be considered.

During the interval between 1 A.M to 5 A.M (interval 1) the small variation of the load requires three ORPF runs. The first run at the beginning of interval 1 (i.e. at 1 A.M.). All controls are adjusted in this run. The second and third run at 2 A.M. and 4 A.M. respectively, only continuous controls are adjusted. During the interval between 5 A.M to 7 A.M., (interval 2) the load has substantial increase. For keeping the system in optimal operating condition, during this interval more runs of the ORPF are necessary. A cycle of 30 minutes may keep the system in optimal condition during this interval. All controls are adjusted in the first ORPF run, first period, and only continuous controls are adjusted in successive periods(i.e. 5.5 A.M. 6 A.M. 6.5 A.M.).

The general steps of an ORPF program for any objective function using the optimization tools introduced in the MATLAB are given in Fig.3.

4. System Study

The Ward and Hall 6-bus power system shown in Fig.3 has been studied for comparing the power and energy loss minimization methods. Its line data and the bus data are given in Tables-1 and 2, respectively. The data in Table-2 corresponds to the full load conditions[5]. The limits of bus voltages, tap settings, shunt capacitors, and generators VAR's are given in Table-3. Fig.5 shows the load forecasting of the network for two hours. The time interval of these two hours is studied. The load level in period one is equal to the peak load, and is reduced in each subsequent period. PLM and ELM algorithms implementation to the problem were used and results are compared in the following subsections. At the beginning of the interval, using algorithm, PLM all control variables are set to minimize P_L^1 ,while in ELM all controls variables are set to minimize E_L.

4.1 Power Loss Minimization

Running the ORPF program, the total power loss of the 6-bus system under full load condition is minimized. The objective function and constraints which are given in equations (1-4) have been used. Load flow study was performed for the base case (full load level) system state. The total power loss for the initial state of this system is 10.97 MW. The power losses after running the ORPF for the two hours are given in Table-4. The optimal values of all the control variables and voltage magnitudes which are calculated for the two hours are given in Table-5. As shown in Tables (4 and 5), the first hour is divided into 3-periods. The third period is (30 minutes) because the load changes in this period is small, (Fig.5), and only one ORPF run at the beginning of this period is enough to keep the system in optimum operation. The second hour is divided into four equal periods (each period has 15 minutes) because the changes in the load are relatively large. The total energy loss achieved by PLM was determined as:

$$E_L = [(P_L^{11} + P_L^{21}) * \frac{1}{4} + P_L^{31} * \frac{1}{2}) +$$

$$(P_L^{12} + P_L^{22} + P_L^{32} + P_L^{42}) * \frac{1}{4})]/2 = 6.42\ MWH$$

One of the problems which was encountered during these studies is the infeasibility of solutions. It is possible that the bus loads in subsequent periods differ too much from those in period one. In these cases the ORPF program can't find any feasible solution by only adjusting continuous control variables, due to limited control action. However, the ELM method doesn't have this problem, since it uses the load forecast to set the discrete variables to values that suitably anticipate the expected load variations.

4.2 Energy Loss Minimization

The 6-bus power system with the same load diagram(Fig-5) is used for the minimization of the energy loss (equation 5). The total energy loss found by the ELM is equal to 6.31 MWH. This value is 1.8% less than the energy loss found in the PLM method (6.42 MWH). The bus voltages and control variables for this method for all the periods are given in Table-6. By comparing the simulation results of Tables 5 and 6 The following observations can be made:

1)The voltage profiles using the ELM are better than those from the PLM method (Fig.6). Thus, the stability of the system from a voltage point of view is much higher in the ELM method.

2)The energy loss in the ELM method for the above system is 1.8% less than that from the PLM.

3)The advantages of the ELM are more apparent when the load changes significantly. In cases where the load profile is almost flat during the hour, ELM gives slightly better results.

4)In cases where the load changes during the next hour are large, coming to feasible solution by the PLM method is not always possible unless adjustments of discrete controls are made. In these cases ELM is more likely to find a feasible solution without such adjustments. The reason is that the load conditions for all periods have been considered in the load flow equations which are enforced as constraints in the ELM formulation. Therefore, the optimal values of the discrete control variables obtained using the ELM method can usually handle the load changes predicted by the load forecast. The only circumstance when ELM cannot find a feasible solution is when the load changes over the given time interval is very different from the predicted values. In these cases, the discrete control variables must be adjusted to avoid voltage violations. This may be avoided by choosing a shorter interval.

5. Conclusion

A new method suitable for optimal reactive power dispatch is proposed. The method minimizes the total energy loss during the next hour, while keeping the voltage profile within an acceptable range. By comparing simulation results, it is found that ELM gives a better voltage profile than that from the PLM method; in the example considered in this work, the method produced a nearly constant voltage profile during the specified hour. In addition, the energy loss was reduced at the same time, with the same number of discrete control variable changes as used by the PLM. The ELM method is based on the recognition that certain control variables should not be adjusted too often, as this may cause wear and shorten the life of the corresponding equipment. In this example, there are two categories of control variables established, the discrete and continuous control variables are adjusted at the beginning of each hour, while during the hour, only the continuous control variables are adjusted. The number of categories could be increased, and the frequency of adjustment modified, to fit different circumstances. The probability of finding an infeasible solution with the ELM method is much lower than the PLM method. This advantage of the ELM method is obtained by considering the load forecast and making sure that anticipated load changes during the next hour can be accommodated.

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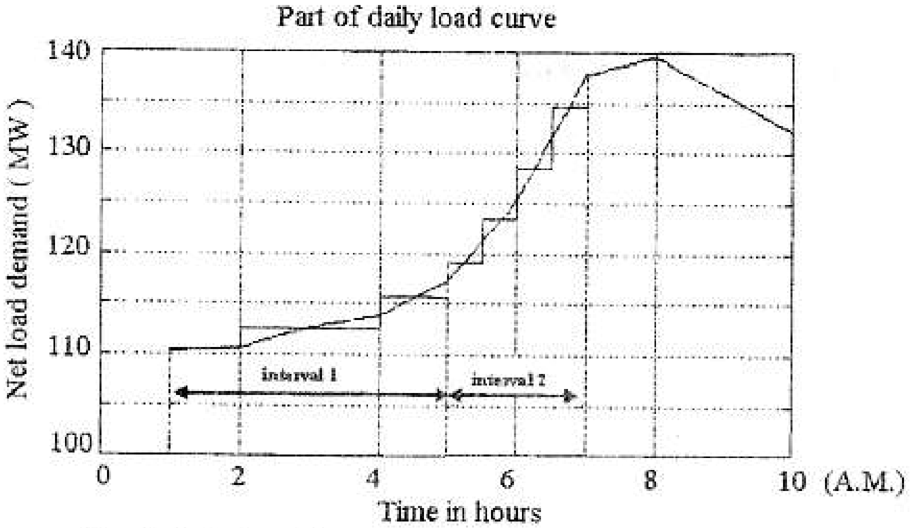


Fig.-1: Selection of intervals and periods for a daily load curve

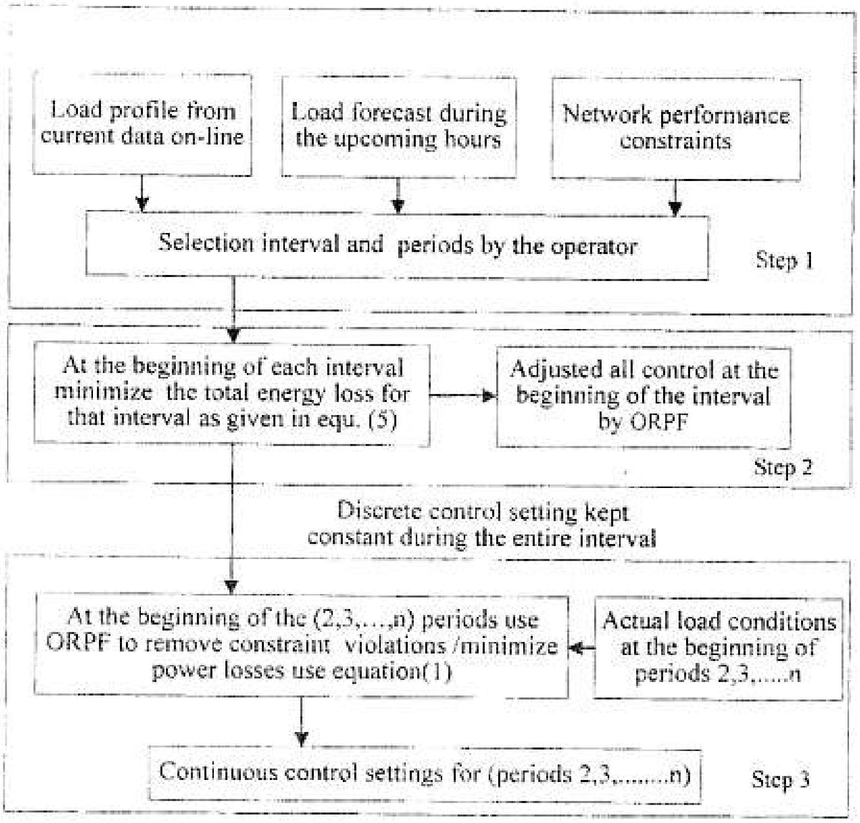


Fig.2: Block diagram of the energy loss minimization method

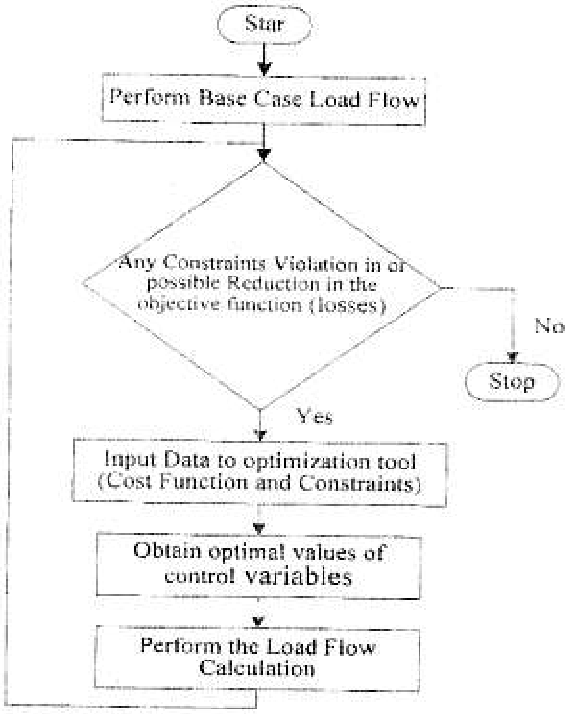


Fig.3: General ORPF algorithm

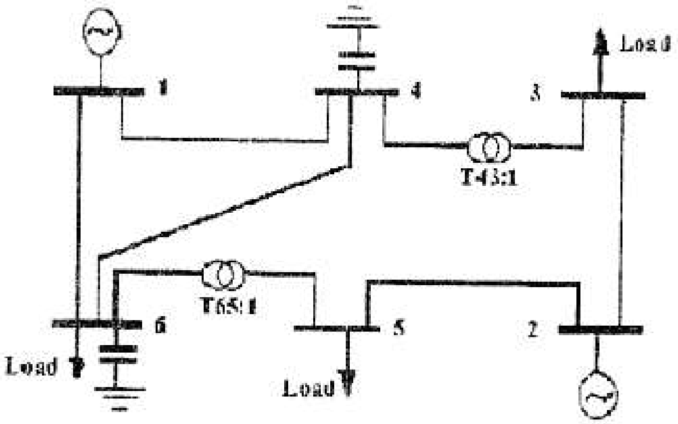
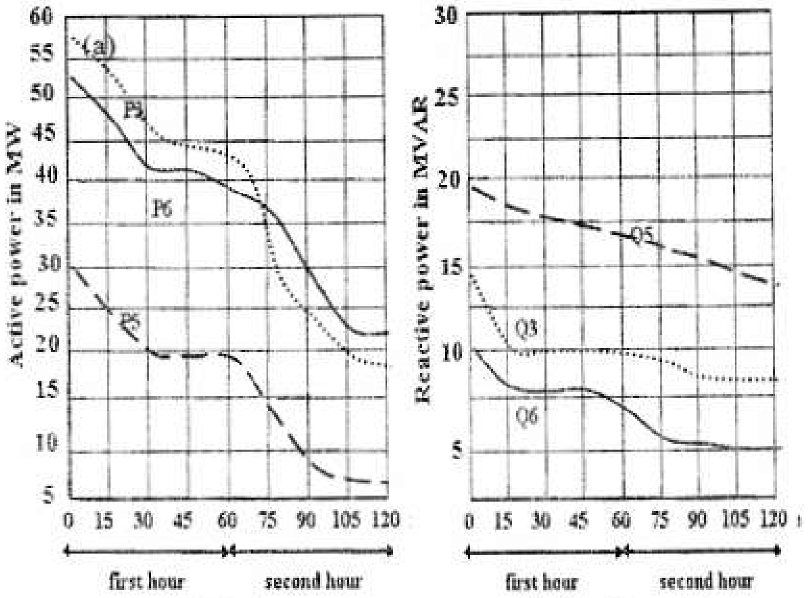
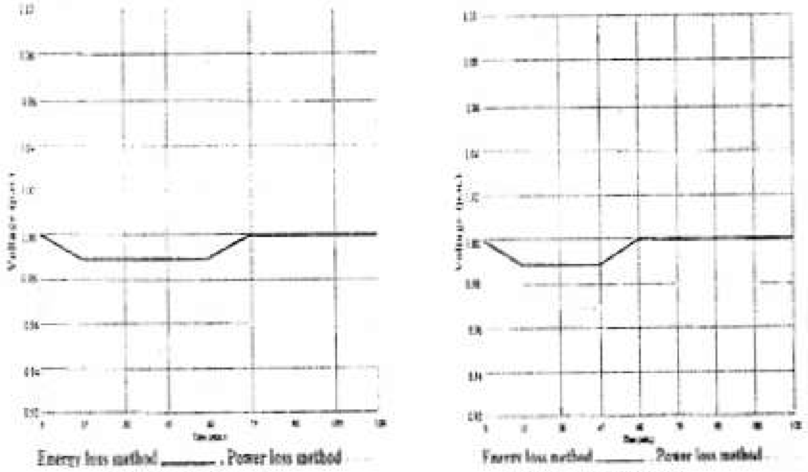


Fig. 4: The Ward and Hale 6-bus power system



(a) Active power (b) Reactive power

Fig-5: Load forecast for two hours.



(a) Bus-4 voltage (b) Bus-6 voltage

Fig.6: Voltage profile from PLM and ELM methods

Table-1: System line data (100MVA base)

Line No.	Bus Number		Impedance(p.u.)		Tap Setting
	From	To	R	X	
1	1	6	0.1223	0.518	1
2	1	4	0.080	0.370	1
3	4	6	0.097	0.407	1
4	6	5	0.000	0.300	1.025
5	5	2	0.282	0.640	1
6	2	3	0.723	1.050	1
7	4	3	0.000	0.133	1.1

Table-2: System bus data

Bus Number	Voltage		Generation		Load	
	V(p.u.)	,deg.	P (MW)	Q (MVAR)	P (MW)	Q (MVAR)
1	1.05	0.0	--	--	0.0	0.0
2	1.10	0.0	50.0	--	0.0	0.0
3	1.00	0.0	--	--	55.0	13.0
4	1.00	0.0	--	--	0.0	0.0
5	1.00	0.0	--	--	30.0	18.0
6	1.00	0.0	--	--	50.0	10.0

Table-3: Limits of system variables

Variable		Limits	
		Low	High
V_{g1}	p.u.	1.00	1.1
V_{g2}		1.10	1.15
V_{l3}		0.95	1.05
V_{l4}		0.95	1.05
V_{l5}		0.95	1.05
V_{l6}		0.95	1.05
T_{43}		0.95	1.05
T_{65}		0.95	1.05
Q_{g1}	MVAR	-20.0	100.0
Q_{g2}		-20.0	100.0
Q_{C4}		0.0	15.0
Q_{C6}		0.0	30.0

Table-4: Power loss for two hours from the PLM method

Interval	First hour			Second hour			
Time period	1 15min.	2 15min.	3 30min.	1 15min.	2 15min.	3 15min.	4 15min.
Power loss(MW)	8.8210	7.6257	6.6505	6.2032	5.3959	4.9205	4.6907

Table-5: PLM method results

Variables	Periods of first hour			Periods of second hour			
	1	2	3	1	2	3	4
T_{43} (p.u.)	0.95	0.95	0.95	0.95	0.95	0.95	0.95
T_{65} (p.u.)	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Q_{C4} (MVAR)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Q_{C6} (MVAR)	30.00	30.00	30.00	15.00	15.00	15.00	15.00
V_{g1} (p.u.)	1.07	1.03	1.00	1.02	1.01	1.00	1.02
V_{g2} (p.u.)	1.10	1.10	1.12	1.10	1.10	1.15	1.12
V_{l3} (p.u.)	1.00	0.99	0.99	1.00	1.00	1.00	1.00
V_{l4} (p.u.)	0.97	0.96	0.95	0.97	0.96	0.96	0.96
V_{l5} (p.u.)	0.99	0.98	1.00	1.00	0.99	0.99	0.99
V_{l6} (p.u.)	0.98	0.98	0.97	0.99	0.98	0.98	0.97

Table-6: ELM method results

Variables	Periods of first hour			Periods of second hour			
	1	2	3	1	2	3	4
T_{43} (p.u.)	0.95	0.95	0.95	0.95	0.95	0.95	0.95
T_{65} (p.u.)	0.98	0.98	0.98	0.95	0.95	0.95	0.95
Q_{C4} (MVAR)	10.00	10.00	10.00	15.00	15.00	15.00	15.00
Q_{C6} (MVAR)	20.00	20.00	20.00	10.00	10.00	10.00	10.00
V_{g1} (p.u.)	1.10	1.07	1.06	1.00	1.01	1.01	1.05
V_{g2} (p.u.)	1.10	1.12	1.12	1.10	1.12	1.11	1.10
V_{l3} (p.u.)	1.00	0.99	0.99	1.00	1.00	1.00	1.00
V_{l4} (p.u.)	1.00	0.99	0.99	0.99	1.00	1.00	1.00
V_{l5} (p.u.)	0.98	0.99	0.99	0.99	0.99	0.99	0.99
V_{l6} (p.u.)	1.00	0.99	0.99	1.00	1.00	1.00	1.00