Ministry of Energy

Esfahan Regional Electric Company

Power System Planning Center

Adaptive Dynamic Load Modeling Method for Esfahan Regional Electrical Network

(Technical Report)

Feb 2013

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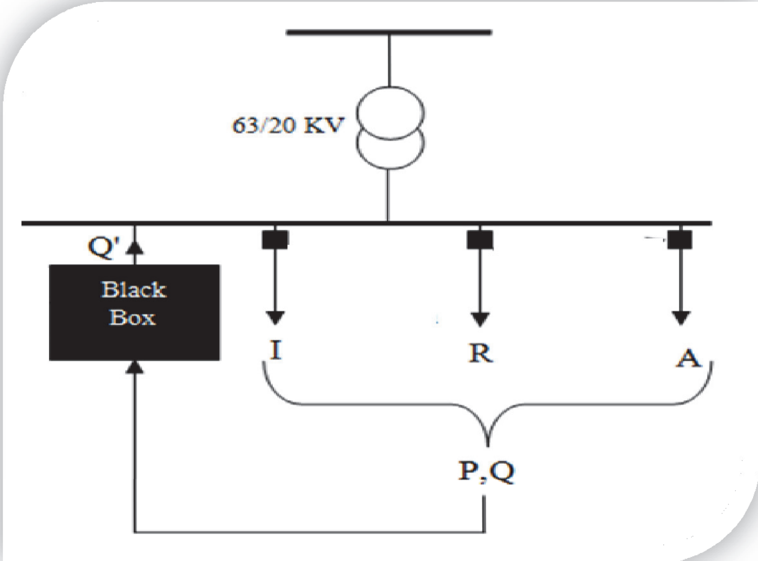

Feb 2013

Prepared by

Load Modeling Research Group

Technical Studies Subcommittee

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Summary

Loads in the power systems are one of the most important parts in the network studies which have been less focused because of shortages and lack of sufficient data. In this report, an adaptive load modeling method is proposed which is useful for large scale power system in order to stability and protection analysis. This method is based on direct measurement method which has been used to record data of some specific 20kV feeders. Furthermore, least square method and Taboo search algorithm have been utilized to form and solve the objective function in presence of problem constrains. Simulation results show the accuracy of the proposed model and modeling method.

1. Introduction

Loads in power system are cumulative consumption of hundreds or thousands industrial, commercial, residential and agriculture consumers. Nowadays, static power system studies are usually based on constant load model specially in Esfahan Regional Electrical Network (EREN). Also, dynamic or transient analysis of power system are usually done considering common dynamic load model which is consist of 80% static and 20% induction motor load models. It is clear that these modeling types don't meet expectations in terms of accuracy and adequacy. In this report, an appropriate load model based on standard models and an adaptive modeling method are proposed which are useful enough for dynamic and protection studies. These model and modeling method are easy to implement in large power networks, has sufficient accuracy and considers practical limitations.

2. Conventional standard load models

Nowadays, standard models are used for power system simulation. Data transfer among different power system software is easier when standard component models are used. There are five standard load models which are more common in power system software:

2.1. static ZIP model

This model consists of three parts including constant power, constant current and constant impedance. Equations of this model for both active and reactive parts can be expressed as below:

$$P_L = P_0\left[a_1(V)^2 + a_2(V) + a_3\right] \quad (1)$$

$$Q_L = Q_0\left[a_4(V)^2 + a_5(V) + a_6\right] \quad (2)$$

Where $a_1 + a_2 + a_3 = 1$, $a_4 + a_5 + a_6 = 1$.

2.2. Motor dynamic model

In this model, active and reactive parts of load are described based on induction motor model as a function of voltage behavior. Fig. 1, shows equivalent circuit for this model.

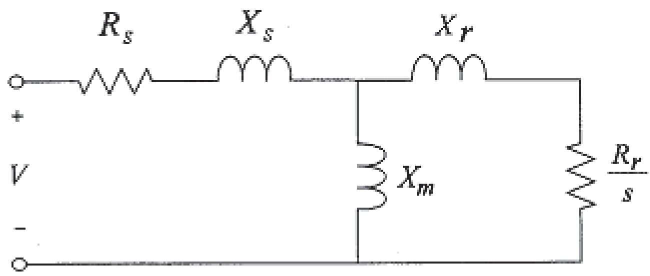

Fig. 1: Induction motor dynamic equivalent model

2.3. Composite model

This model is combination of static ZIP and motor Dynamic model as Fig. 2.

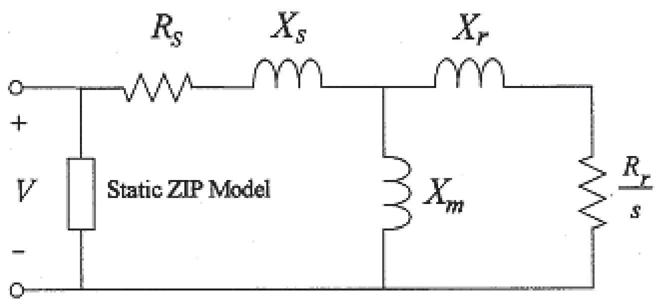

Fig. 2: Composite load model

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2.4. PTIIEEE model

Load dependency on voltage and frequency are considered in this model. This model is an improved version of static ZIP model which has an additional linear term that shows the frequency deviation (Δf) from its nominal value. Model's equations can be expressed as below:

$$P_L = P_0\left[a_1(V)^{K1} + a_2(V)^{K2} + a_3(V)^{K3}\right]\ (1 + a_4\Delta f) \tag{3}$$

$$Q_L = Q_0\left[a_5(V)^{K4} + a_6(V)^{K5} + a_7(V)^{K6}\right]\ (1 + a_8\Delta f) \tag{4}$$

Furthermore, there are some models like PTIIEEE which are composed of a static term and two terms which are dependent on voltage and frequency.

2.5. Exponential model

This is a simplified exponential model which is voltage dependent and can be used for combination loads but its parameters are much less than PTIIEEE model and its accuracy is much less respectively. Model equations are:

$$P_L = P_0(\frac{V}{V_0})^{KPV} \tag{5}$$

$$Q_L = Q_0(\frac{V}{V_0})^{KQV} \tag{6}$$

3. Appropriate load models for different types of power system studies

In this part, appropriate models for static, stability and protection studies will be discussed considering specific characters of each load model.

3.1. Appropriate model for static studies of power system

Appropriate model for static studies of power system is one that obviously demonstrate voltage dependency of loads. Among standard models, static ZIP model can be selected as an appropriate model. It should be noted that software must be able to detect the static part of load model from its dynamic part. In the other words, PTIIEEE model also can be selected for static studies but software must be able to consider frequency deviation equal to zero.

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3.2. Appropriate model for stability studies of power system

Multiple modeling should be used for dynamic, transient, long term and small signal stability analysis of power system. Multiple modeling means demonstrating and modeling all type of loads which are located in a single busbar such as all kind of one or three phase induction motors, synchronous motors and static loads. Furthermore, WECC has proposed that reactive power resources, feeders and transformers should be modeled exactly in presence of protection scheme. Fig. 3, shows WECC's model.

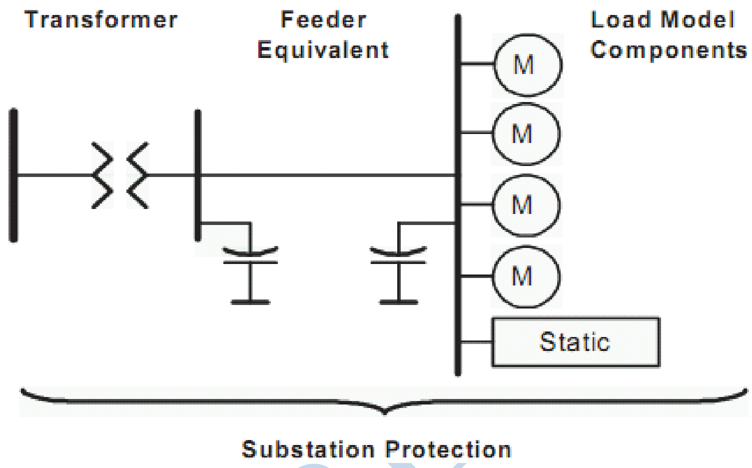

Fig. 3: Multiple modeling method

In this model, If accurate data of system loads are not available (for example motor parameters), dynamic parts of model can be replaced by PTIIEEE model. In the other words, PTIIEEE model can be used for motors model respectively.

3.3. Appropriate model for protection studies of power system

Load model effects on protection studies have been investigated before. This effect can be seen on fault impedance, entrance angle to protection zone, blocking time and swing curve during fault occurrence. It is fixed when the motor dynamic model or composite load model is used, significant fluctuations can be observed outside the protection zone. Generally, if the main protection in power system is distance protection, load model will effect on distance relay sittings. In this regard, following models have better performance in power system simulation during protection studies respectively.

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- PTIIEEE
- Static ZIP model
- Exponential model
- Dynamic motor model
- composite model

Therefore, PTIIEEE model is more suitable than other models for protection studies.

4. Load modeling methods

After the determination of load model type, it is necessary to extract the model parameters which is the biggest challenge in load modeling procedure. Generally, there are two methods for determining the model's parameters. Each of them needs particular collections of data which can be so time consuming. These methods are components modeling method and measurement method.

4.1. Components modeling method

In this method, load components model make the load model. This is the best method for load modeling, but it is far more difficult and time consumer than any other methods because all loads (which contain many consumers) would be analyzed exactly and their components should be determined crystal clear. For example, in residential load type, the amount of refrigerators, chillers, lightings and other ordinary consumption must be specified exactly. Also, in industrial load type, the amount of 3 or 1 phase induction motors and their inertia, power electronic consumption, constant impedance, current and power loads should be reconnoitered. These procedures would be repeated for different conditions as peak and off peak and also for different areas of power system. Since consumption regimes will vary with the change of seasons, mentioned procedure must be repeated regularly. Therefore, it can be seen that this method is so expensive and also needs a huge time to collect required data.

4.2. Measurement method

Measurement method is based on direct measurement of power system variables such as voltage and frequency deviations from their nominal values with the amount of active and reactive power for specific periods of time. These data are collected for all load types (industrial, agricultural, residential and commercial loads) by measuring variable of the particular feeders which supply specific loads. Hence, by fitting data to the model's equations, typical model for each load type can be obtained. An appropriate load model can be obtained by combining these load types based on the amount of each one for any specific busbar load. The main advantages of this method are:

- ✓ Typical models can be applied for load modeling in all busbars and it would also results in less time and cost than load component modeling method.
- ✓ This model uses real data which can be ideal for determination of model's parameters.

On the other hand, it is not possible to make an acceptable model for a long time using measured data in some special time periods which it is the main drawback of this method.

5. Proposed method

Figure 4 shows the current load model in EREN which is constant power load model. Figure 5 shows the proposed load model which supports dynamic operations of power system loads. The proposed load model and modeling method for EREN have been suggested in the way that this model can be used for different types of power system studies with reasonable accuracy. This modeling is described in the following steps.

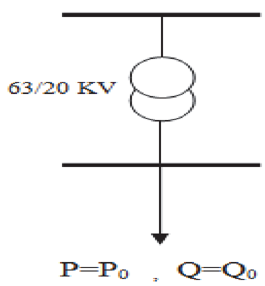

Figure 4: Current load model in EREN

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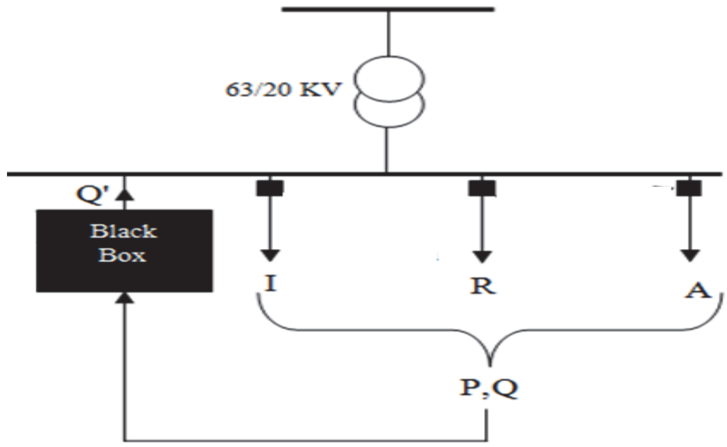

Figure 5: proposed load model

5.1. Load classification

Each cumulative load would be divided to three groups: Agricultural, industrial and residential-commercial load. Nowadays, air conditions are used widely in residential consumptions while it was only used for commercial consumptions before. Therefore, it is possible to consider residential and commercial loads in one group because of their similar behavior. Fig 5, shows this classification. As it has shown in this Figure, in this model three types of loads are used instead of single constant load. These types are residential-commercial (R), industrial (I) and agricultural (A).

5.2. Capacitor bank modeling

Distribution loads in EREN are modeled in 20KV side of sub-transmission substations. Furthermore, there are switchable capacitor banks in 20KV side of these substations to fix power factor in acceptable range. Therefore, dynamic capacitor bank modeling is necessary for Long Term Dynamic (LTD) studies which has less considered in load modeling before. Different references have only modeled static behavior of capacitors. In this report, dynamic modeling of capacitor banks will be performed. Black box in Fig 5, reflects the function of capacitor bank in load behavior.

5.3. model selection

According to the standard load models (part 2) and their applications (part 3), PTIIEEE model is suitable for almost all types of power system studies. The final formulation of selected model are as bellow.

$$P_L = P_0\left[x_1(\frac{V}{V_0})^2 + x_2(\frac{V}{V_0})^{x_3} + (1 - x_1 - x_2)(\frac{V}{V_0})^{x_4}\right] \times (1 + x_5.(\frac{f - f_0}{f_0})) \tag{7}$$

$$Q_L = Q_0\left[x_6(\frac{V}{V_0})^2 + x_7(\frac{V}{V_0})^{x_8} + (1 - x_6 - x_7)(\frac{V}{V_0})^{x_9}\right] \times (1 + x_{10}.(\frac{f - f_0}{f_0})) \tag{8}$$

Where P,Q,V and f are active power, reactive power , voltage and frequency respectively. Index 0 shows the initial values of the variables. Selected model is consist of one constant impedance term and two exponential terms. Also a linear term is used to describe the frequency dependant of loads. In above equations, model's passive coefficients are x_i which should be calculated during modeling procedure.

5.4. Modeling method selection

As described in section 2, load component method takes too much time and cost. Hence, measurement method is selected as modeling method in order to calculate model's unknown coefficients.

6. Data collection

Data collection is concerned to three groups as bellow:

6.1. Special measurement on some specific feeders

High accurate measurements are required in order to determine the voltage and frequency dependency of loads. Also, the sampling rate should be high enough because large time gap between two samples decreases the accuracy of modeling. Measurements devices (IPF9600) has installed on some specific feeders. IPF9600 can record data in maximum rate of 2 samples per cycle. Table 1 shows selected feeders which supply special load types.

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Table 1: Selected feeders for setup recorder devices

Substation	KNM7002	KNM8014	KNM8084
Selected feeder	6	8	1
Load type	Industrial	Residential-Commercial	Agricultural

Operational maneuver on tap changer can help to determine voltage dependency better and better. Therefore, during data recording, tap position was increased and then decreased in two steps as shown in Figure 6. Frequency, active and reactive power also are shown in this Figure. These data have been collected from the candidate feeder of KNM7002 substation.

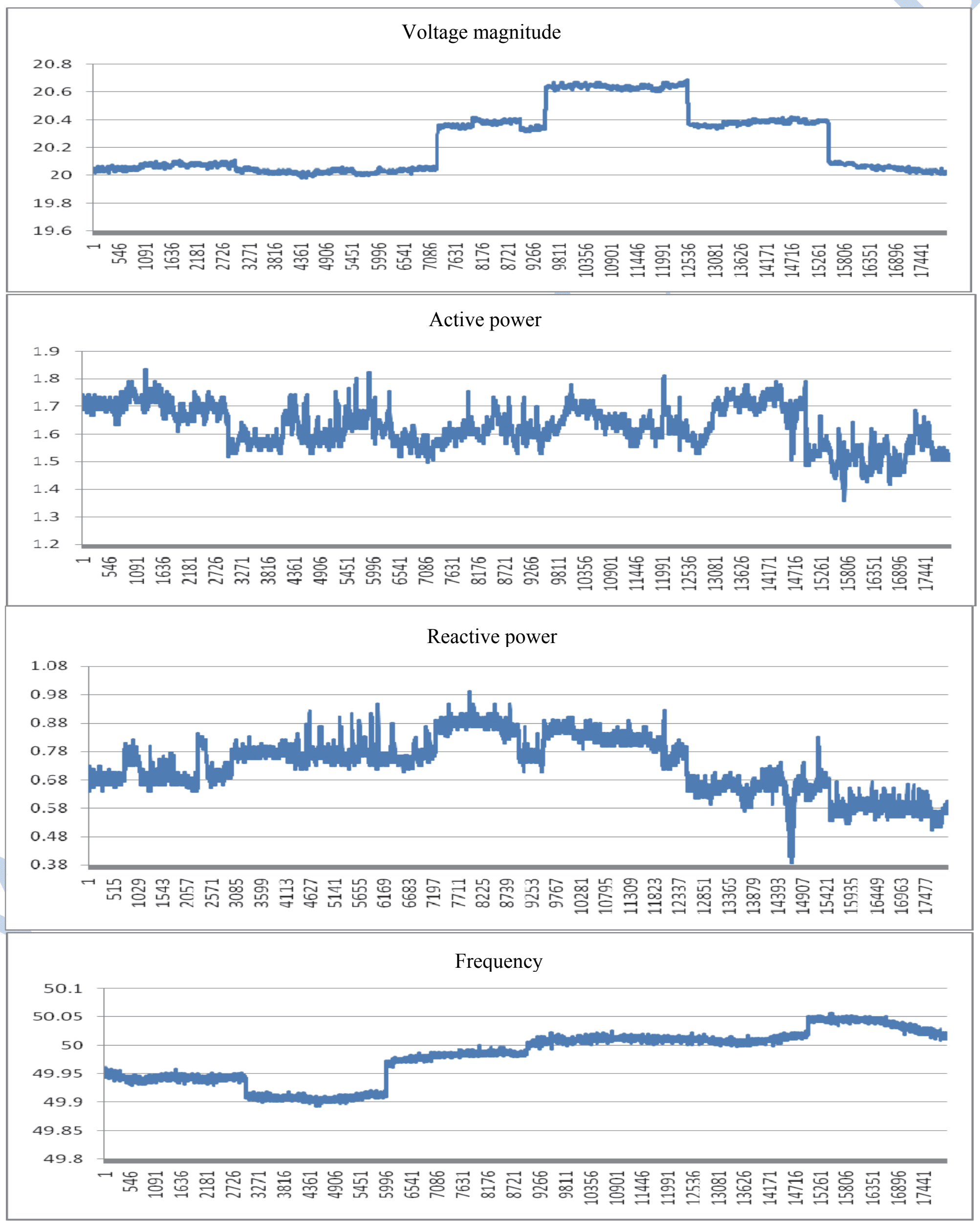

Figure 6: Recorded data from an industrial feeder

6.2. Determination of load type percent on each substation

Load type percent on each substation has been determined by examining consumer electricity tariffs through the distribution company for 115 substations in EREN. Table 2 shows load type percent on some of these substations.

Table 2: determination of load type percent on some substations

Substation	Residential-commercial (%)	Agricultural (%)	Industrial (%)
KNM5052	31.77	33.78	34.45
KNM5028	57.43	8.11	3.46
KNM6069	39.61	2.22	58.17

6.3.Achievement to the logic of capacitor banks

Capacitor banks in EREN usually have 6 steps. Each one is 2.7 MVAR. Thus, there are 16.2 MVAR reactive power potential for each capacitor bank. Total injected reactive power of capacitors is depended on total power factor (PF) of busbar load and its logic is based on following desirable PF (PF=1). There is a suitable delay in each step in order to prevent continues tension of capacitors. Also, capacitor units are choosing in the way that capacitor aging be same for all capacitor units.

7. Adaptive analysis method

As mentioned before, after selection of model, model' parameters must be calculated. The main challenge is determination of data analysis method. In this report, whereas there are so many recorded data and based on structure of selected model, an adaptive analysis method based on least square method is used to estimate model's parameters. This adaptive method converts the main problem to an optimization problem with appropriate objective function and suitable constraints.

7.1. Least square method

Least square is an effective method to solve a set of equations which its equations are far more than its passive parameters. In this method, we try to minimize the sum of squared residuals. Residual in this method is difference between the observed value and the value calculated from the model.

There are some classical method to solve the objective function such as lasso, ridge regression and etc. But extremely nonlinear equations cannot be solved attentively by classical methods. In the other words, estimation variance of passive parameter for nonlinear equations will increase acutely. Hence, intelligent search algorithms would be applied to solve this kind of problems. In this article Taboo search algorithm is used as a method based to solve the problem.

7.2. Taboo search algorithm

Taboo search algorithm moves to optimal solution based on move to least value around the initial answer guess which is randomly generated. Points around the initial value are called neighborhood. Algorithm is designed in the way that all solution space could be checked. So, jump to other appropriate initial guess is done after specific movements. Number of neighborhoods and jumps are fundamental parameters of this algorithm which should be detected regarding the solution space and the kind of problem.

8. Objective functions

Objective functions and their constraints are formed based on least square method. They can be expressed for active power model by (9)-(12):

$$\min \sum_{i=2}^{N} \left(P_i^{Real} - P_i^{Cal}\right)^2 \tag{9}$$

$$P_i^{Cal} = P_{i-1}^{Real} \times \left[x_1 \left(\frac{V_i}{V_{i-1}}\right)^2 + x_2 \left(\frac{V_i}{V_{i-1}}\right)^{x_3} + (1 - x_1 - x_2)\left(\frac{V_i}{V_{i-1}}\right)^{x_4} \right] \times \left(1 + x_5 . \left(\frac{f_i - f_{i-1}}{f_{i-1}}\right)\right) \tag{10}$$

Subject to:

$$x_i > 0 \qquad , i = 1,2,3,4,5 \tag{11}$$

$$x_1 + x_2 \leq 1 \tag{12}$$

And for reactive power by (13)-(16):

$$\min \sum_{i=2}^{N} \left(Q_i^{Real} - Q_i^{Cal}\right)^2 \tag{13}$$

$$Q_i^{Cal} = Q_{i-1}^{Real} \times \left[x_6 \left(\frac{V_i}{V_{i-1}}\right)^2 + x_7 \left(\frac{V_i}{V_{i-1}}\right)^{x_8} + (1 - x_1 - x_2)\left(\frac{V_i}{V_{i-1}}\right)^{x_9} \right] \times \left(1 + x_{10} . \left(\frac{f_i - f_{i-1}}{f_{i-1}}\right)\right) \tag{16}$$

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Subject to:

$$x_i > 0 \quad , i = 6,7,8,9,10 \tag{17}$$

$$x_6 + x_7 \leq 1 \tag{18}$$

Where:

P_i^{Real} , P_i^{Cal} are measured and calculated active power for i-th instant.

Q_i^{Real} , Q_i^{Cal} are measured and calculated reactive power for i-th instant.

V_i , f_i are measured voltage and frequency for i-th instant.

N is the number of recorded data over the modeling time period. Modeling time period contains one or several 30 second periods which include peak load and tap changing conditions. In order to reach to high modeling accuracy, P_{i-1}, V_{i-1} and f_{i-1} are considered as P_0, V_0 and f_0. Table 3 shows the fundamental parameters of Taboo search algorithm.

Table 3: Fundamental parameter of taboo search algorithm

Parameter	neighborhood	movement	jump
size	20	20	20

9.Numerical results

Figure 7 and Figure 8 show the instant calculation results of Taboo search algorithm to find active power model's coefficients for agricultural load type and reactive power model's coefficients for industrial load type respectively.

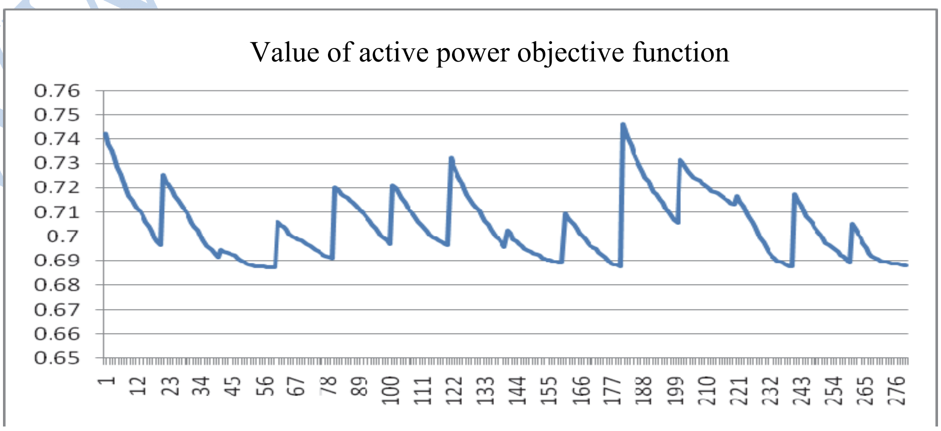

Figure 7: Taboo search results to find active power coefficients of agricultural load type

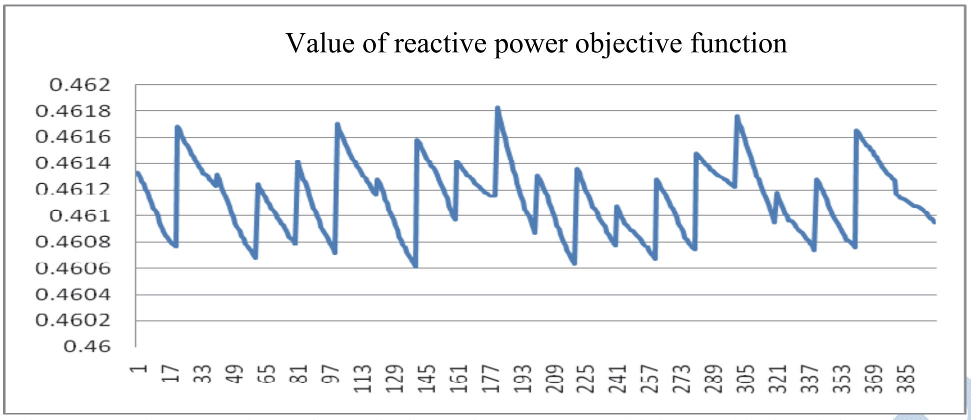

Figure 8: Taboo search results to find reactive power coefficients of industrial load type

It can be seen that Taboo search algorithm has been succeeded to meet optimal value for model's passive factors. Movements and jumps are obviously visible. Table 4 shows the final quantities of selected model.

Table 4: final quantity of proposed model

Load	Coefficient	Industrial Type	Agricultural Type	Residential-Commercial Type
Active power	x_1	0.095	0.056	0.122
	x_2	0.599	0.460	0.378
	x_3	0.623	0.150	0.829
	x_4	0.828	0.103	3.031
	x_5	3.432	1.169	0.457
Reactive power	x_6	0.004	0.115	0.314
	x_7	0.423	0.544	0.012
	x_8	0.327	0.457	0.869
	x_9	0.001	2.564	2.491
	x_{10}	3.765	2.585	0.841

10. Model confirmation

In order to confirm the model and extracted coefficients, real measured data and calculated values based on proposed model for a 30 seconds time period are shown in Figure 9. Furthermore, measured voltage and frequency are also shown. It can be seen that almost calculated values follow the load behavior especially when power is increasing or decreasing due to change in voltage and frequency. Anyway, there are differences between real and calculated values sometimes which are at the result of change in base load level (p_0). In the other words, model uses the calculated value of previous moment (P_{i-1}^{Cal}) as the base load level (p_0) to estimate new value of power and is not able to distinguish the time dependency of p_0. While, generally base load level is time dependent as bellow: $p_0 = p_0(t)$ (19)

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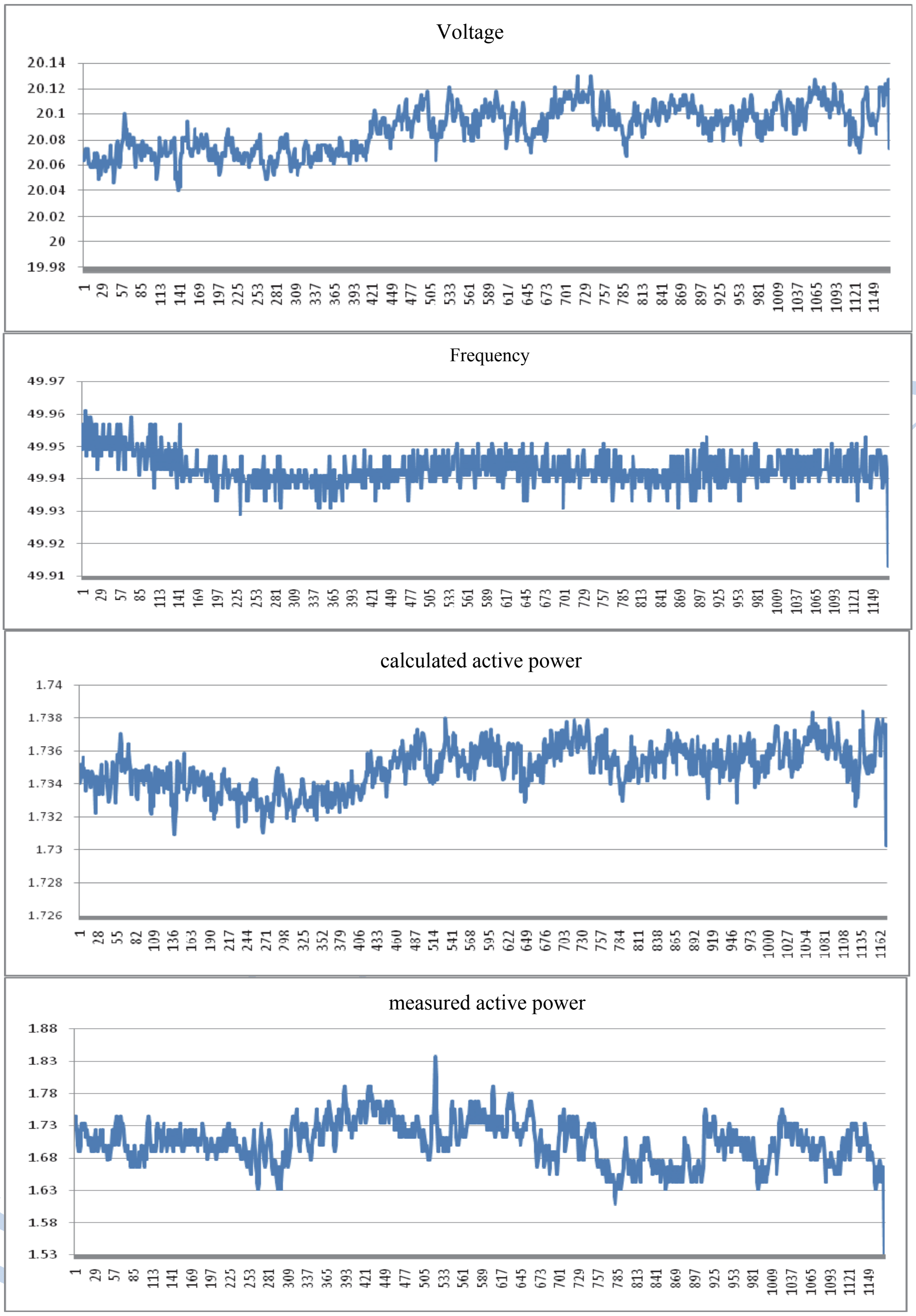

Figure 9: real measured data and calculated values based on proposed method for a 30 seconds time period

Furthermore, it is necessary to have an appropriate index to compare proposed load model with constant load model. In this report, following indexes are defined and applied to show the differences between two models.

$$T_{Cal} = \sum_{i=2}^{N} \left(P_i^{\mathrm{Re}\ al} - P_i^{Cal}\right)^2 \tag{20}$$

$$T_{Consant} = \sum_{i=2}^{N} \left(P_i^{\mathrm{Re}\ al} - P_{Average}\right)^2 \tag{21}$$

Where:

T_{Cal} is least square considering proposed model.

P_i^{Cal} is calculated power by (10).

$T_{Consant}$ is least square considering constant load model.

$P_{Average}$ is average value of power during measurement time period.

Table 5 shows the numerical compression between constant and proposed load model.

Table 5: Numerical compression between constant and PTIIEEE load model

Time period	Date	$T_{Costant}$	T_{Cal}
11:45:00-11:45:30	08/21/2012	2.003959	1.875057
11:55:00-11:55:30	08/21/2012	1.814837	1.761548
13:25:00-13:25:30	08/21/2012	2.212279	1.125606
16:30:00-16:30:30	08/21/2012	2.154214	0.713947

It can be seen that proposed load model is much better than constant load model in following real behavior of load.

11. Simulation results of capacitor banks operation

As mentioned before, dynamic simulation of capacitor banks operation has a main effect on LTD studies. Figure 10 shows the absorbed reactive power of black box in the period of 50 seconds for 20KV side of KNM8084 substation. Figure 11 shows the power factor and Figure 12 shows the voltage magnitude of mentioned busbar during simulation. It can be seen that 4 steps of capacitor bank have entered to improve total power factor and voltage magnitude of the busbar.

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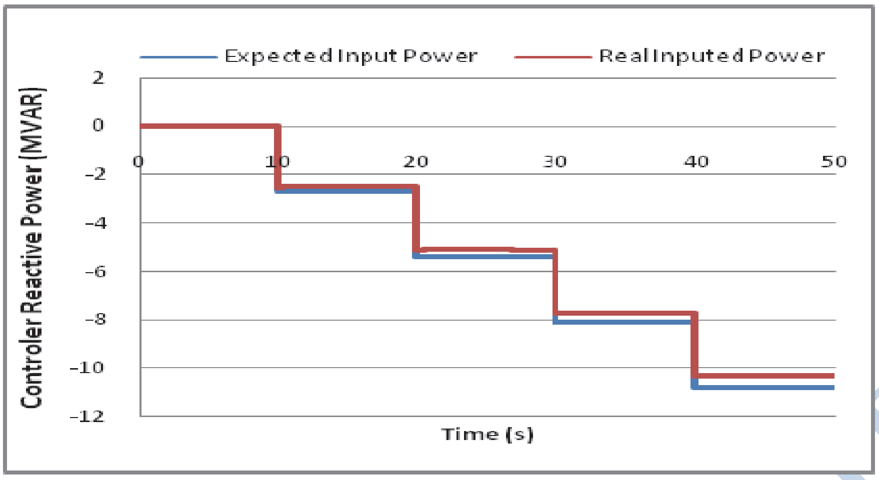

Figure 10: Expected and real input reactive power of capacitor bank

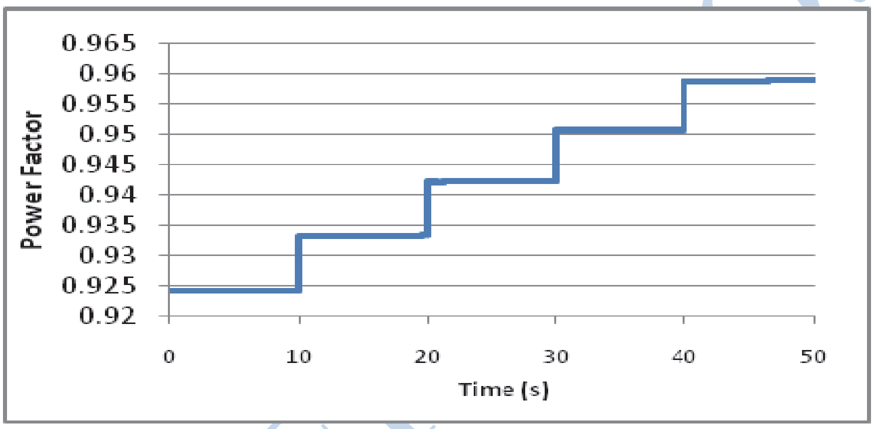

Figure 11: Power factor correction considering dynamic behavior of capacitor bank

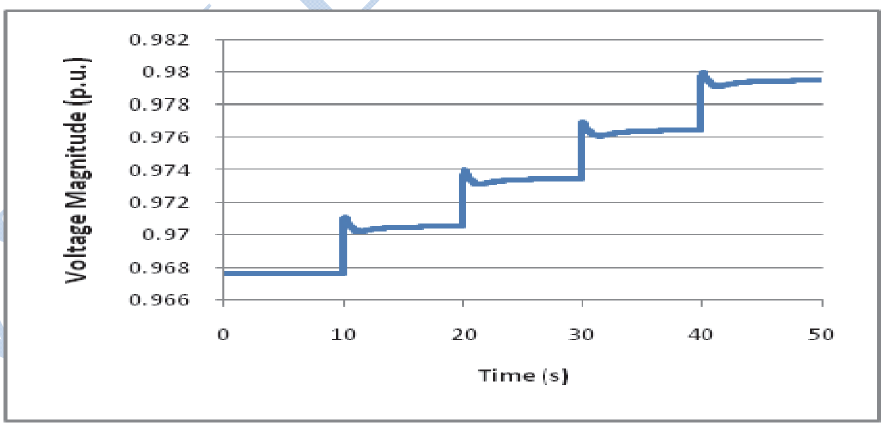

Figure 12: Voltage magnitude considering dynamic behavior of capacitor bank

Expected input power in Figure 10, is the amount of reactive power that should be injected to network considering 1 p.u voltage magnitude but, it varies due to change in the voltage magnitude of busbar which is called real injected power.

12. proposed Load model effect on power system studies

In this section, short circuit clearing time is checked considering constant power load model and proposed load model. Figure 13 shows voltage behavior during a three phases short circuit which is cleared after 200 milliseconds at KNM7002 63KV busbar of EREN. Dynamic system equipments such as governors, excitations and etc are modeled exactly.

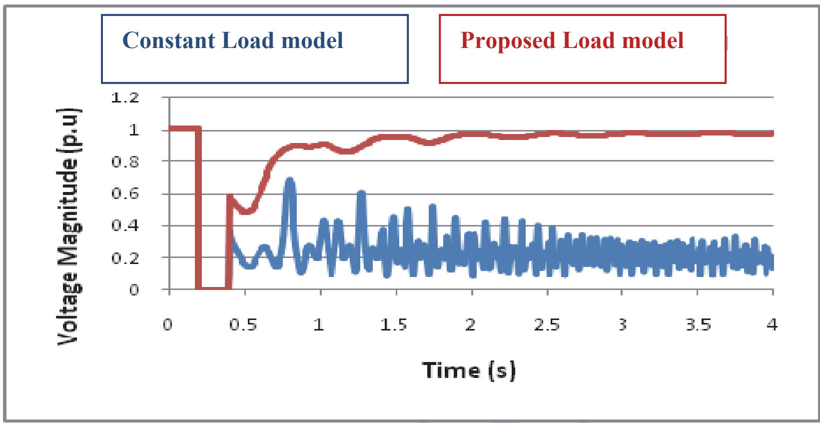

Figure 13: voltage behavior during a three phases short circuit

As can be seen, using the constant power load model will result in voltage collapse while applying proposed load model will result in safe voltage recovery. Hence, appropriate load model and adaptive modeling method can improve the accuracy of dynamic studies and modify the stability criteria.

13.Conclusion

In this report, a general review on conventional load models, modeling method and also appropriate load models for each type of power system studies were done. Regarding the all aspects of modeling, specific PTIIEEE load model finally was proposed to model loads in EREN. Direct measurement method was used to collect required data during reasonable maneuvers on tap changer position. Least square method was applied to form objective function and Taboo search algorithm was used to find model's coefficients. Furthermore, behavior of capacitor banks was exactly modeled in order to increase the accuracy of LTD studies. Finally, proposed model was evaluated comparing with real recorded data. Also, a quantitative index was defined to compare constant power with the proposed load model numerically. Results has shown that proposed model reflects the load behavior better than constant load model in various types of power system studies such as protection, stability, LTD and etc. Since dissimilar loads such as industrial, residential-commercial and agricultural are modeled separately, it is easy to correct their amount pending various load level and simulation time.