Loads and Synchronous Generator Modeling

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***Abstract*-- This paper survey of different accurate models of load and synchronous generator model. I would like to described one out of two basic types of load modeling. One is component-based load modeling which contain 'ZIP' (polynomial) model, exponential model, combination of this two called exponential-'ZIP' model and ETMSP & EPRI model as an example of combination of fundamental models. Second one is measurement-based load modeling, however, this is not on my consideration. The second part survey consists synchronous generator modeling by electrical circuits. Moreover, there are dc generators, but this model is not covered in this paper.**

I. INTRODUCTION

There are two general issues to consider modeling of power systems. One of them is loads modeling as well as generators modeling. Loads and generators modeling are very important in determining the stability of power systems. Moreover there are valuable tools in the stability studies.

Load modeling application can be distinguished into static and dynamic models. First of all I would like to shortly describe static load model. The static models were discovered to investigate steady-state power systems. In this models occurs constant voltage magnitude, but on the other hand there is variation of load frequency. Lastly the static load models feature is voltage-dependent characteristic. Second of all it is mentioned in the technical literature about dynamic load modeling. This load model is in time-domain and contains loads electromechanical behavior. Phasors method is the load steady-state representation. The dynamic load model is based on time variation frequency. Moreover, the dynamic load model is describe by dynamic voltage and frequency characteristics.[1]

The second part of this paper is to survey generators modeling. The Generators can be classified as a electrical motors. There are dc generators, synchronous generators and inductor generators. The dc generators are rarely used in power systems. The most popular and common use in the industrial applications is synchronous generator. There have been developed big number of synchronous generators. The generators are the heart of power systems. " With the increasing cost of detailed prototyping of electrical machine, it is becoming necessary to replace or supplement it with mathematical methods and computer simulation."[2] However, the inductor generators are used in power systems, but mostly in wind turbines. The number of wind turbines connected to the grid increase every year. Papers [8], [9], [10] are contained more information`s about double fed induction generators modeling.

II. LOAD MODELING

Load modeling is a very important issue in power system analysis and control. Accurate load models have significant impact on the operations flexibility and exploitation costs in power systems. Exploitation costs can be reduced because of there is possible to test new solution and change power system configuration without any disturbances of normal power system work. The operations flexibility is also very important regarding to beater fit power system modeling into real power system. That is why both power industry and academia are looking for now, and more accurate loads representation. We can distinguish two approaches for load models developing: component-based and measurement-based. "The component-based approach builds a load model using detailed information about all the individual components at each load bus. The measurement-based approach involves placing measurement systems at the load buses for which load models are to be developed."[3] The measurement-based approach gives us actual load behaviors at any given moment. In the power industry is also used on-line data recording system. This tool gives important information about actual load behaviors during system disturbances. Dynamic load models regarding to possible disturbances response are highly recommended for a lot of power system models representations, moreover this models are commonly used in power industry for transient stability analysis. On the other hand, it increases of system representation for simulation. [3]

Loads modeling has always been a difficult issue because:

- many different types of load are connected to the power system at any period of time,
- level of complication and quantity of data is very high at any given moment,
- it is hard to predict loads response (behavior), [4]

We can distinguish three main load models:

- ✓ 'ZIP' (polynomial) model,
- ✓ exponential model and
- ✓ exponential – 'ZIP' model - combination of this two above [1]

A. Polynomial-'ZIP' Model

One of the oldest load representation is polynomial model. It is essentially combination of constant impedance (Z), constant current (I) and constant power (P), that is why it is commonly called 'ZIP' model. This model is not accurate representation of the system, because of high number of inductor motor loads in the system. Nowadays there are more complex and accurate load models which capture both the static and dynamic load, such as induction motors.[4]

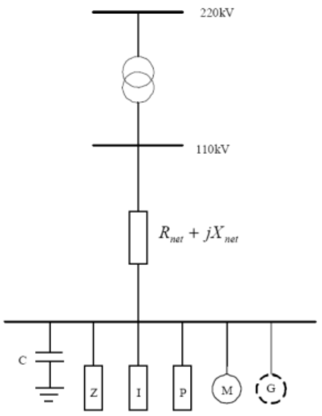

Fig.1. The structure of 'ZIP' load model. [5]

$$P_L = P_0\left[p_1\left(\frac{V}{V_0}\right)^2 + p_2\left(\frac{V}{V_0}\right)^1 + p_3\right]\left(1 + K_{pf}\Delta f\right)$$

$$Q_L = Q_0\left[q_1\left(\frac{V}{V_0}\right)^2 + q_2\left(\frac{V}{V_0}\right)^1 + q_3\right]\left(1 + K_{qf}\Delta f\right)$$

p_1 and q_1 are the constant impedance load parameters,
p_2 and q_2 are the constant current load parameters,
p_3 and q_3 are the constant power load parameters,
K_{pf} and K_{pf} are the frequency sensitivity parameters,
and $p_1 + p_2 + p_3 = 1$, $q_1 + q_2 + q_3 = 1$ when $V = V_0$. [2]

B. Exponential Model

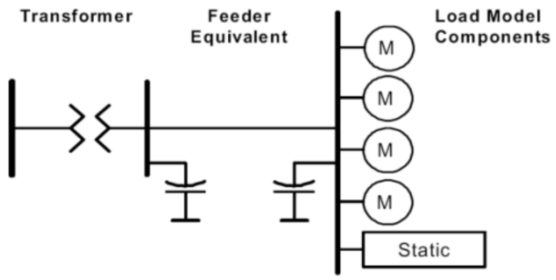

Fig.2. The structure of any static load models.[6]

This scheme can be used for any static load modeling. So, it fit for every presented in this paper load model.

$$P_L = P_0\left(\frac{V}{V_0}\right)^{K_{pV}}\left(1 + K_{pf}\Delta f\right)$$

$$Q_L = Q_0\left(\frac{V}{V_0}\right)^{K_{qV}}\left(1 + K_{qf}\Delta f\right)$$

K_{pV} -voltage-dependent parameter of real power,
K_{qV} -voltage-dependent parameter of reactive power,
K_{pf} and K_{pf} are the frequency sensitivity parameters.[3]
Comparing of 'ZIP' and exponential load modeling the second one is more accurate.

C. Exponential-'ZIP' Model

This is the combination of both exponential and 'ZIP' models which are shown above. Diagram can be the same as in previous model.

$$\frac{P}{P_0} = \left(1 + \left(K_{pi} + K_{pc} + K_{p1} + K_{p2}\right)\right)\left(\frac{V}{V_0}\right)^2 + \\ + K_{pi}\left(\frac{V}{V_0}\right) + K_{pc} + K_{p1}\left(\frac{V}{V_0}\right)^{npv1} \times \left(1 + K_{pf1}\Delta f\right) \\ + K_{p2}\left(\frac{V}{V_0}\right)^{npv2}\left(1 + K_{pf2}\Delta f\right)$$

$$\frac{Q}{Q_0} = \left(1 + \left(K_{qi} + K_{qc} + K_{q1} + K_{q2}\right)\right)\left(\frac{V}{V_0}\right)^2 + \\ + K_{qi}\left(\frac{V}{V_0}\right) + K_{qc} + K_{q1}\left(\frac{V}{V_0}\right)^{nqv1} \times \left(1 + K_{qf1}\Delta f\right) \\ + K_{q2}\left(\frac{V}{V_0}\right)^{nqv2}\left(1 + K_{qf2}\Delta f\right)$$

K_{pi} and K_{qi} are the constant current parts of the total load,
K_{pc} and K_{qc} are the constant power parts of the total load,
K_{p1}, K_{pf1}, $npv1$, K_{p2}, K_{pf2}, $npv2$, K_{q1}, K_{qf1}, $nqv1$, K_{q2}, K_{qf2}, $nqv2$ are the parameters of exponential part of the total load.[3]

D. ETMSP & EPRI Model

Scheme is shown in Fig.2. However, there are some more models discoverd by the companies. The companies which have made distribution system computers programs (software). They have used this three types of load modeling and modify them. EPRI's LOADSYN and ETMSP packages are one of the most commonly used software for dynamic studies. This two packages based on load models presented above with little changes. Below the result of this changes is shown:

$$P_L = P_0\left\{P_{a1}\left(\frac{V}{V_0}\right)^{K_{pv1}}\left(1 + K_{pf1}\Delta f\right) + \left(1 - P_{a1}\right)\left(\frac{V}{V_0}\right)^{K_{pv2}}\right\}$$

$$Q_L = P_0\left\{Q_{a1}\left(\frac{V}{V_0}\right)^{K_{qv1}}\left(1 + K_{qf1}\Delta f\right) \\ + \left(\frac{Q_0}{P_0} - Q_{a1}\right)\left(\frac{V}{V_0}\right)^{K_{qv2}}\left(1 + K_{qf2}\Delta f\right)\right\}$$

where,
P_{a1} is the frequency dependent fraction of real load,
Q_{a1} is the reactive load coefficient of uncompensated reactive load to real power load,
K_{pv1} and K_{pv2} are the voltage exponents for frequency-dependent and frequency-independent real power load,
K_{qv1} and K_{qv2} the voltage exponents for the uncompensated and compensated reactive power load,
K_{pf1} and K_{pf2} are the frequency sensitivity coefficients for real and uncompensated reactive power load
K_{qf2} is the frequency sensitivity coefficient for reactive compensation [3].

We have showed this load model as a example of one combination of this fundamental models.

III. GENERATORS MODELING

Generators convert mechanical energy to electrical energy. There are three possible types of generators: dc generators, induction generators and synchronous generators. The first one are useless because all the power systems around the world are AC. So there are two main types of generators: one of them is synchronous generator and second is induction generator. The inductor generators mostly occur in the wind mills. The synchronous generators are common use in most types of power plants.

First of all the synchronous machines work with constant speed what means constant frequency. The speed of the synchronous generator linearly depends on the frequency and numbers of poles. The constant frequency is very good feature because one of the power systems requirements is to keep frequency in one specified level. Another advantage comes from reactive power compensation in the grid. The synchronous generators produce active power and reactive power. The last important feature is high efficiency of synchronous generators.

The inductor generators are less popular then the synchronous generators. However, they have some advantages. One of them is that inductor generators are simplified in construction. Furthermore, they are lighter and cheaper than any others. However the frequency cannot be adjusted as simple as in the synchronous generator and the reactive power cannot be compensated. When one would like to use inductor generator it should also have special control system. The speed controllers are going to be cheaper and cheaper and inductor generators are commonly used in the wind mills.

I would like to present synchronous generator modeling by electrical circuits. There are more synchronous generators models in papers [7],[11], [12], [13].

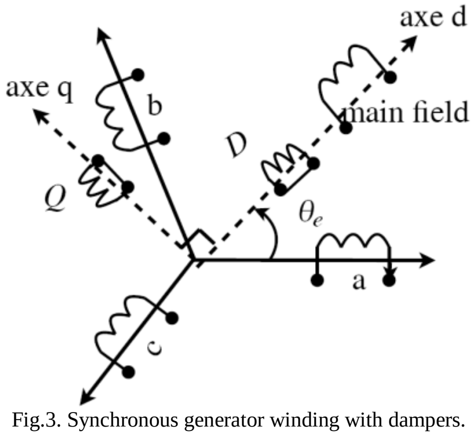

Fig.3. Synchronous generator winding with dampers.

D and Q represent d-axis and q-axis dampers. The three synchronous generator modeling methods presented below are based on this scheme.[2]

A. *Synchronous Generators Modeling by Electrical Circuit*

From figure above the machine equations in three axis framework is shown below:

$$v_{abc} = -r_s i_{abc} + \frac{d}{dt}\Psi_{abc}$$
$$v_f = r_f i_f + \frac{d}{dt}\Psi_f$$
$$0 = r_D i_D + \frac{d}{dt}\Psi_D$$
$$0 = r_Q i_Q + \frac{d}{dt}\Psi_Q$$

i_D and i_Q are the direct and transverse dumpers` currents,
i_f is the exciter current,
Ψ_D and Ψ_Q are the direct and transverse dumpers` total flux,
Ψ_{abc} is the stator total flux,
Ψ_f is the main field total flux,
The Park`s matrix can be written as:

$$P(\theta_e) = \sqrt{\frac{2}{3}}\begin{bmatrix} cos(\theta_e) & cos\left(\theta_e - \frac{2\pi}{3}\right) & cos\left(\theta_e + \frac{2\pi}{3}\right) \\ -sin(\theta_e) & -sin\left(\theta_e - \frac{2\pi}{3}\right) & -sin\left(\theta_e + \frac{2\pi}{3}\right) \end{bmatrix}$$

$$P(\theta_e)\cdot v_{abc} = P(\theta_e)\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} v_d \\ v_q \end{bmatrix}$$

We can rewrite first equations as:

$$v_d = -r_s i_d + \frac{d}{dt}\Psi_d - \omega_e \Psi_q$$
$$v_q = -r_s i_d + \frac{d}{dt}\Psi_q - \omega_e \Psi_d$$
$$v_f = r_f i_f + \frac{d}{dt}\Psi_f$$
$$0 = r_D i_D + \frac{d}{dt}\Psi_D$$
$$0 = r_Q i_Q + \frac{d}{dt}\Psi_Q$$

Then the following relationships can be written considering the generator convention for stator

$$\begin{cases} \Psi_d = \Psi_{ad} + \Psi_{\sigma sd} + \Psi_{\sigma fd} = \\ = l_{ad}\left(-i_d + i_D + i_f\right) - l_{\sigma sd} i_d + l_{\sigma fd}\left(i_f - i_d\right) \\ \Psi_q = \Psi_{aq} + \Psi_{\sigma sq} = \\ = l_{aq}\left(-i_q + i_Q\right) - l_{\sigma sq} i_q \\ \Psi_f = \Psi_{ad} + \Psi_{\sigma f} + \Psi_{\sigma fd} = \\ = l_{ad}\left(-i_d + i_D + i_f\right) + l_{\sigma f} i_f + l_{\sigma fd}\left(i_f - i_d\right) \\ \Psi_D = \Psi_{ad} + \Psi_{\sigma D} = \\ = l_{ad}\left(-i_d + i_D + i_f\right) + l_{\sigma D} i_D \\ \Psi_Q = \Psi_{aq} + \Psi_{\sigma Q} = \\ = l_{aq}\left(-i_q + i_Q\right) - l_{\sigma Q} i_Q \end{cases}$$

From all this equations we can draw the synchronous machine electrical scheme as follows:

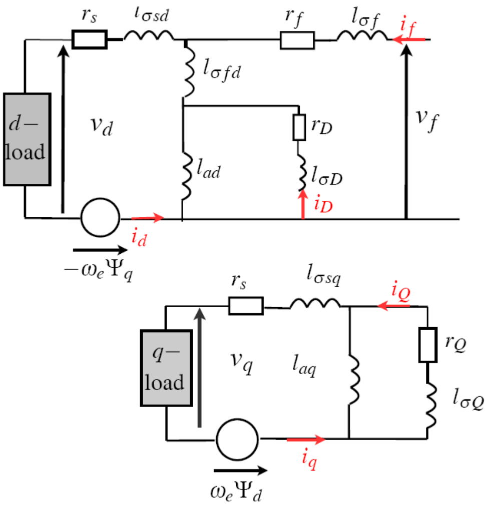

Fig.4. d-axis and q-axis electrical equivalent circuits. [2]

$\Psi_{\sigma f}$ is the rotor leakage flux,
$\Psi_{\sigma D}$ and $\Psi_{\sigma Q}$ are direct and transverse dampers leakage flux,
$\Psi_{\sigma sd}$ and $\Psi_{\sigma sq}$ are direct and transverse stator dampers leakage flux,
$\Psi_{\sigma fd}$ is the linkage flux between main field and stator d-axis,
Ψ_{ad} and Ψ_{aq} are direct and transverse main flux,
$l_{\sigma sd}$ and $l_{\sigma sq}$ are direct and transverse stator leakage inductances,
$l_{\sigma f}$ is the rotor main field leakage inductance,
l_{ad} and l_{aq} are the direct and transverse stator main inductances,
$l_{\sigma D}$ and $l_{\sigma Q}$ are dampers leakage inductances,
$l_{\sigma fd}$ is the linkage inductance between the rotor main field and the stator d-axis,

In these scheme the linkage inductance between d-axis stator and direct damper is neglected. "In the Fig.4. the blocks "d-load" and "q-load" represent the equivalent loads in Park`s framework of the real power factor load. This last is star-connected and an inverse Park`s transformation is needed to elaborate "d-load" and "q-load". This is useful because all equations involved in the simulation are given in Park`s framework" [2]

IV. CONCLUSIONS

In this paper, different accurate models of load and generation were examined. As a load models component-based load modeling were shown which contain 'ZIP' (polynomial) model, exponential model, exponential-'ZIP' model and ETMSP & EPRI model as a example of combination of fundamental models. All models examined in this paper are static load models. The static load models can be used for approximation of the dynamic behavior of the power system. Moreover static nonlinear load models can be used for transient stability analysis. However this model is not appropriate for capturing true load response and for industrial applications measurement-based models are required. 'ZIP' model gives only approximate results of real power behavior. Exponential model is more accurate and has only two parameters to be estimated. Exponential-'ZIP' model is also very promising but it is a little bit more complex what can give unwanted confusion [3]. "With continued expansion of power grid, it becomes more and more important that the model used in simulation programs consist with the actual characteristics of electric apparatus. Up to now, the model of generators, transformers and power lines have been established perfectly, as for the model of load, due to its randomness, time-varying and distribution property, it could barely describe the whole characteristics exactly by one or more groups of equations. Accurate load modeling has become one of the most difficult problems in power system research fields."[5]

Second part of the survey consists synchronous generator model by electrical circuit. This model consists the global electrical scheme of the generator by flux equations. Paper [2] contains tests of the three synchronous generator models which can be distinguished into: synchronous generator modeling by electrical circuits, by state equations using an inside load and by state equations using an outside load.

V. REFERENCES

[1] Prabha Kundur, "Power System Stability and Control", 2007
[2] Emile MOUNI, Slim TNANI and Gérard CHAMPENOIS, "Comparative study of three modeling methods of synchronous generator.", IEEE, 2006
[3] Y. Li, H.-D. Chiang, B.-K. Choi, Y.-T. Chen, D.-H. Huang and M.G. Lauby, "Representative static load models for transient stability analysis: development and examination", IET Gener. Transm. Distrib., 2007, 1, (3), pp. 422–431
[4] A. Maitra, A. Gaikwad, P. Pourbeik, D. Brooks, "Load Model Parameter Derivation Using an Automated Algorithm and Measured Data", IEEE, 2008
[5] Jingchao Zhang Anhe Yan Zhuoya Chen and Kun Gao, "Dynamic Synthesis Load Modeling Approach Based on Load Survey and Load Curves Analysis", IEEE, DRPT2008 6-9 April 2008 Nanjing China
[6] Dmitry Kosterev, Anatoliy Meklin, "Load Modeling in WECC", IEEE, 2006
[7] Emile Mouni, Slim Tnani and Gérard Champenois, "Synchronous generator output voltage control via a generalized predictive R S T controller.", IEEE, 2008
[8] E. Spahic', J. Morren', G. Balzer and G. Michalke, "Mathematical Model of the Double Fed Induction Generator for Wind Turbines and its Control Quality", IEEE, POWERENG 2007, April 12-14, 2007, Setubal, Portugal
[9] Srinivas R. Chellapilla, Badml H. Chowdhury, "A Dynamic model of Induction Generators for Wind Power Studies", IEEE, 2003
[10] José Cidrás and Andrés Elías Feijóo, "A Linear Dynamic Model for Asynchronous Wind Turbines With Mechanical Fluctuations", IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 17, NO. 3, AUGUST 2002
[11] J. R. Marti and K. W. Louie, "A Phase-Domain Synchronous Generator Model Including Saturation Effects, IEEE Transactions on Power Systems, Vol. 12, No. 1, February 1997
[12] E. Lu, G. Bronner, A. Ilk, C. Neumeyer, S. Ramakrishnan, "MODEL for TFTR Motor-Generator (MG)", IEEE, Princeton, New Jersey, 1995
[13] Zhijun Li and Lijuan Cui, "The Building and Analyzing of the Fifth-Order Model of the Synchronous Generator in Stand-Alone Infinite System", IEEE, 2005