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TENSOR-BASED APPROACH IN MODELING OF POWER SYSTEMS WITH DISTRIBUTED GENERATION FOR STABILITY ANALYSIS TASK

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Abstract: Actual trend of increase number of distributed generation causes necessity of review mathematical methods, using for electromagnetic process description. Electromagnetic energy connects different parts of multi-energy power system. The power system is multidimensional also. Therefore, it needs valid and multidimensional methods. Present modeling in stability estimation task focus on parameters of power system mode. An alternative approach is necessary. Energy, its types, physical quantities are primary. This paper focuses on analysis of energy flow processes and existing mathematical models. In order to estimate and analyze stability of power system we use tensor approach. In this paper we present results of analysis and first steps to building tensor-based model, focus on energy flow processes. In addition, we focus on invertor connected sources of energy, such as solar and wind generation. It aimed on future equations set-up, which are use tensor based approach.

1. INTRODUCTION

Actual trend of increase number of distributed generation cause growth of dimensions ("curse of dimensionality"). So, it's necessary to review mathematical methods, using for electromagnetic processes description. In addition, appearance and increase number of distributed generation sources intensify and complicate stability analysis task.

Since the emergence of electromagnetic theory, it is carrying out work on its application in industry. It's bidirectional process. One of examples is electrical power system. It is one of the largest electromagnetic systems. Appearance of large power systems cause problem of its stability.

Modeling approaches, their completeness are cause validity of results in many respects. So, development methods and approaches in modeling have caused considerable recent research interest.

Electromagnetic energy connects different parts of multi-energy power system. In addition, distributed generation use different types of primary energy sources, therefore, different technologies of generation. The transmission of different energy types, involved in generation and consumption, realizing through electromagnetic energy. The power system is multidimensional also. Therefore, it is need multidimensional methods, which validly describe specifics of electric power system with distributed generation sources of different generating technologies.

A method to validate computational electromagnetics computer modeling and simulation techniques, codes, and models is defined in standard [4]. It is applicable to a wide variety of electromagnetic applications including, but not limited to, the fields of electromagnetic compatibility, radar cross section, signal integrity, and antennas. Examples and problem sets to be used in the validation of computational electromagnetics (CEM) computer modeling and simulation techniques, codes, and models are provided in [5].

Stability of power system is important area in research. Recommendations [6] present excitation system and power system stabilizer models suitable for use in large-scale system stability studies. In [3] categorizes three direct-axis and four quadrature-axis models, along with the basic transient reactance model. Some of the assumptions made in using various models are discussed and presents of the fundamental equations with concepts of generator/system interfacing are involved.

Recently, increase number of distributed generation and their impact on stability of power systems is a current problem. In [10] reviewed impact of distributed generation on transient stability, and it was found that the effects of distributed generation on the dynamics of a power system strongly depend on the technology of the distributed generators. The suggestions about supplementing control system algorithm of power system with distributed generation sources for concern of their dynamic properties are made in [11]. This supplementing aimed on improving stability.

Multicriteria optimization is important task in power system modeling. In [2] the solution of the topological task is suggested to represent in the form of the Pareto-optimal area.

Appearance of distributed generation and increase its number complicate modeling. Therefore, approach on modeling should be improved. Tensor approach is not new. Different areas of circuit analysis used this method over long time. A method for designing transformation electromagnetics devices using tensor impedance surfaces is presented in [9]. In paper [7], a tensor-based big data management scheme is proposed for dimensionality reduction problem of big data generated from various smart devices.

However, practical using of tensor approach in power systems stability analysis was far from complete.

Present modeling in stability estimation task focus on parameters of power system mode. An alternative approach is necessary. Energy, its types, physical quantities are primary. As concerns power system, it's parameters of system and quantities, describing parameters of electromagnetic energy. In addition, appearance of distributed generation and increase its number complicate modeling. First of all, specifics of different types of primary energy and its transformation must be considered through modeling. The second problem is increasing dimension.

This paper focuses on analysis of energy flow processes and existing mathematical models. In order to estimate and analyze stability of power system we use tensor approach. In this paper we present results of analysis and first steps to building tensor-based model, focus on energy flow processes.

2. CLASSIFICATION SOURCES OF ENERGY AND STABILITY ANALYSIS TASK

In general, the steady-state stability of the system can be achieved if an increase (decrease) in mechanical power causes a corresponding increase (decrease) in electrical power, because mechanical and electrical powers must become balanced [1]. System of differential equations [1] using for small signal stability analysis of power system (also it called small oscillations, small hunting)

$$\begin{cases} T_{J1}\dfrac{d^2\Delta\delta_1}{dt^2}+\dfrac{\partial P_1}{\partial\delta_{12}}\Delta\delta_{12}+\ldots+\dfrac{\partial P_1}{\partial\delta_{1M}}\Delta\delta_{1M}=0, \\ T_{J2}\dfrac{d^2\Delta\delta_2}{dt^2}+\dfrac{\partial P_2}{\partial\delta_{12}}\Delta\delta_{12}+\ldots+\dfrac{\partial P_2}{\partial\delta_{1M}}\Delta\delta_{1M}=0, \\ \vdots \\ T_{JM}\dfrac{d^2\Delta\delta_M}{dt^2}+\dfrac{\partial P_M}{\partial\delta_{12}}\Delta\delta_{12}+\ldots+\dfrac{\partial P_M}{\partial\delta_{1M}}\Delta\delta_{1M}=0 \end{cases} \tag{1}$$

Generation of electric energy uses different types generating technologies. Generally, type of primary energy determines type of source. Information in table 1 represents classification of sources by type, which are considered in our research. It should be noted, that classification is made in terms of energy types, especially types of electromagnetic energy, and their transforming. Energy transformation row represents energy flow between parts of power system. AC and DC represent alternating and direct current in terms occurring of electromagnetic energy.

Table 1. Classification of distributed generation sources

Classification type	Non inverter power sources		
Generator type	Turbogenerator	Hydropower plant generator	Wind turbine generator
Energy transformation	Energy of fossil fuel, biomass or nuclear energy ↓ Electromagnetic energy (AC)	Energy of water ↓ Electromagnetic energy (AC)	Energy of wind ↓ Electromagnetic energy (AC)

Dependence stability limits, expressed an angle δ_{12}, represent by power-angle curve shown on Figure 1 and was presented in [11]. The appearance of unstable state condition in power system is possible, when stability limit becomes lower than power limits. This dependence obtained for two equivalent machine system, using equations (1).

It is important to note, increasing number of generators (M) cause increasing number of equations. It leads to obstruct of analysis. In addition, it's focus on parameters of power system mode, but not on real physical quantities. It is not so good, taking into account multi-energy nature of power system.

Identification of physical quantities, involved in energy transformation process, should made in line with information stated in table 1 and table 2.

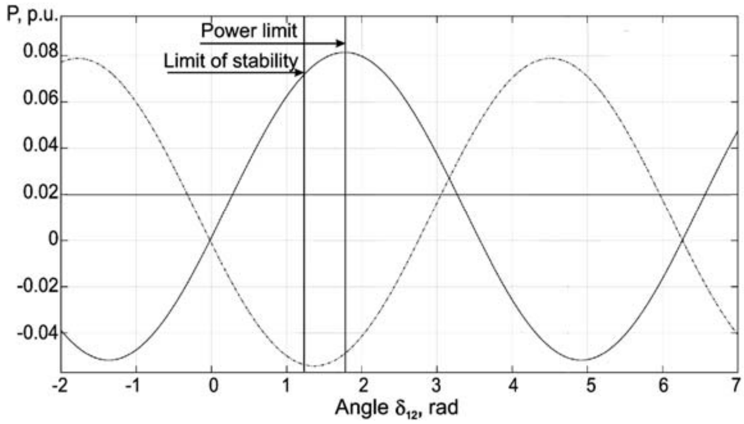

Figure 1. Power-angle graph represents unstable state of power system

Table 2. Classification of distributed generation sources

Classification type	Inverter-connected power sources		
Generator type	Photovoltaic converter	Wind turbine generator	Fuel cell
Energy transformation	Energy of solar radiation ↓ Electromagnetic energy (DC) ↓ Electromagnetic energy (AC)	Energy of wind ↓ Kinetic energy ↓ Electromagnetic energy (AC) ↓ Electromagnetic energy (DC) ↓ Electromagnetic energy (AC)	Chemical energy ↓ Electromagnetic energy (DC) ↓ Electromagnetic energy (AC)

3. MATHEMATICAL MODEL AND RESULTS

According to terms of tensor analysis, each physical quantity represents as tensor. This quantities describes processes, occurring in system, and own properties.

Great number of works, focus on application tensor calculus to electrical machines describing, are exist at present. When the air gap is smooth and windings along the d and q axes are identical, the primitive machine describes by tensors [8]

$$\mathbf{Z} = \begin{array}{|c|c|c|c|} \hline r_S + L_S p & Mp & 0 & 0 \\ \hline Mp & r_r + L_r p & L_r p\theta & Mp\theta \\ \hline -Mp\theta & L_r p & r_r + L_r p & Mp \\ \hline 0 & 0 & Mp & r_S + L_S p \\ \hline \end{array} \qquad (2)$$

$$\mathbf{G} = \begin{array}{|c|c|c|c|} \hline 0 & 0 & L_r & M \\ \hline -M & -L_r & 0 & 0 \\ \hline \end{array} \qquad (3)$$

$$\mathbf{e} = \begin{array}{|c|c|c|c|} \hline e_{ds} & e_{dr} & e_{qr} & e_{qs} \\ \hline \end{array} \qquad (4)$$

Synchronous generator is general type of energy source. It is non-inverter power source. When both stator and rotor axes rotate with the rotor, elementary synchronous machine describes by tensors [8]

$$\mathbf{Z} = \begin{array}{|c|c|} \hline r_f + L_f p & Mp \\ \hline M(p + jp\theta) & r_a + L_a(p + jp\theta) \\ \hline \end{array} \tag{5}$$

$$\mathbf{G} = \begin{array}{|c|c|} \hline 0 & 0 \\ \hline jM & jL_a \\ \hline \end{array} \tag{6}$$

$$\mathbf{e} = \begin{array}{|c|} \hline e_f \\ \hline e_a \\ \hline \end{array} \tag{7}$$

Founding on tensors (2) – (7), components of equations (8) – (11) are set-up [8]. Stability analysis consists on estimation and analyzing of small oscillations.

In case of small oscillations, the speed of rotor pθ is not constant. The equations of impressed voltage (e) and torque (T) of the primitive machine [8]

$$\mathbf{e} = \mathbf{R} \cdot \mathbf{i} + \mathbf{L} \cdot p\mathbf{i} + p\theta\mathbf{G} \cdot \mathbf{i} \tag{8}$$

$$\mathbf{T} = \mathbf{M}p^2\theta - \mathbf{i} \cdot \mathbf{G} \cdot \mathbf{i} \tag{9}$$

The equations of hunting of primitive machine [8]

$$\mathbf{e} = \mathbf{R} \cdot \mathbf{i} + \mathbf{L} \cdot p\mathbf{i} + p\theta\mathbf{G} \cdot \mathbf{i} \tag{10}$$

$$\Delta\mathbf{T} = \mathbf{M}p^2\Delta\theta - \mathbf{i_0} \cdot (\mathbf{G} + \mathbf{G_t}) \cdot \Delta\mathbf{i} \tag{11}$$

The Δ symbol represents fluctuate of quantities, during small oscillations (hunting) in power system.

Stability analysis of power system made on the basis of equations (10), (11).

By analyzing of tensor models of machines, generalization of processes and associated tensors are proposed on figures below. It's important to identify processes, connections between elements, energy flow and associated quantities. This is first step to building tensor-based model.

The non-inverter power source is described on Figure 2. As usual, it's synchronous generator. E(P), E(K) and E(AC) represents primary, kinetic and electromagnetic (alternating current) energy.

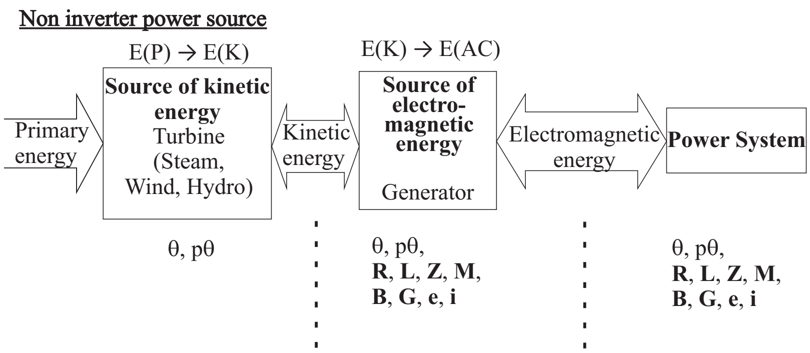

Figure 2. Representation of processes in non-inverter power source

By analogy approach, according to terms of tensor analysis, description of processes and associated tensors in inverter-connected power sources propose on Figure 3.

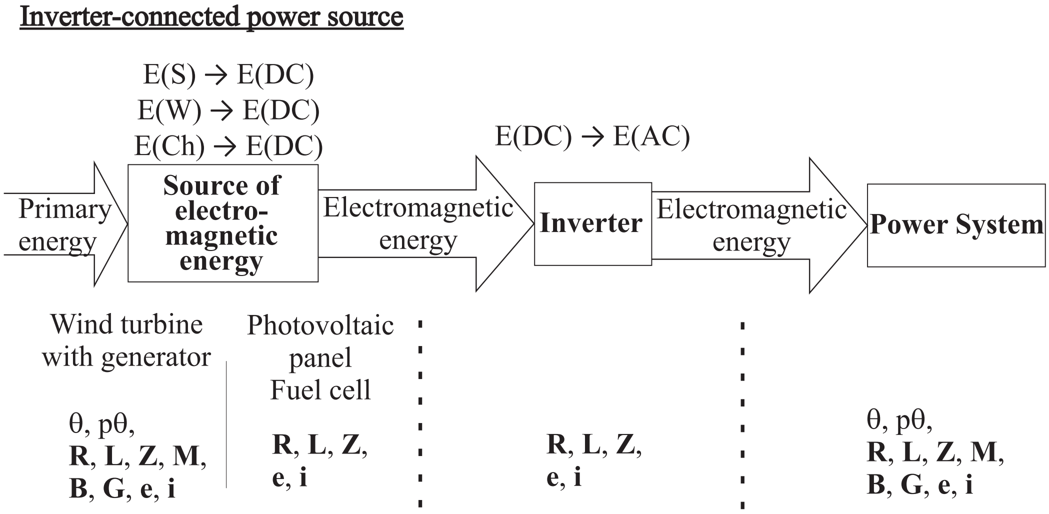

Figure 3. Representation of processes in inverter-connected power source

The inverter-connected power source is described on Figure 3. As usual, it's different types of distributed generation sources. E(S), E(W) and E(Ch) represents solar (radiation intensity, angle between rays and panel of converter, temperature, wind velocity), wind (wind velocity, angularity of turbine blades) and chemical (energy of chemical reaction) energy. E(DC) represents electromagnetic (direct current) energy.

On Figure 2 and Figure 3 the tensors **R**, **L**, **Z**, **M** represents properties of system, tensors **B**, **G**, **e**, **i** describe processes in system.

According to stated above, dependencies for output voltage for solar and wind generation sources may be written in general form.

$$e = f(S, W, t) \tag{12}$$

$$e = f(W) \tag{13}$$

S (solar radiation intensity), *W* (wind velocity) and *t* (temperature) may be obtained from meteorological data or through local measurements. Quantities *S, W, t,* according to tensor approach, naturally should be represented as tensors **S**, **W**, **t**. Important to note, tensor **W** used in both types of generation, solar and wind. It’s additionally justifying tensor approach: identical tensors, representing physical quantities, used in different technical systems.

It should be noted, solar and wind generation is invertor connected, as usually. Therefore, models should include model of invertor and control system dependencies. Switching of transistors process may be represents through transformation matrix.

Quantities and terms, used in table 1, table 2, Figure 2 and Figure 3, represent tensors of associated values. Processes in multi energy system are described. It aimed on future equations set-up, which are use tensor based approach.

5. CONCLUSION

Actual trend of increase number of distributed generation causes complications for modeling. First of all, specifics of different types of primary energy and its transformation must be considered through modeling. The second problem is increasing dimension.

Present modeling in stability estimation task focus on parameters of power system mode, but not on real physical quantities. It is not best way, taking into account multi-energy nature of power system. An alternative approach is necessary. Energy, its types, physical quantities are primary. As concerns power system, it's parameters of system and quantities, describing parameters of different types of energy. This paper focuses on analysis of energy flow processes and existing mathematical models.

According to terms of tensor analysis, each physical quantity represents as tensor. This quantities describes processes, occurring in system, and own properties.

By analyzing of tensor models of machines, generalization of processes and associated tensors are proposed. It's important to identify processes, connections between elements, energy flow and associated quantities. This is the first step to build tensor-based model.

For stability estimation task the initial work on building full mathematical model are made by using tensor-based approach. Quantities and terms, used in table 1, table 2, Figure 2 and Figure 3, represents tensors of associated values. It aimed on future equations set-up, which are use tensor based approach.

This paper proposes application to energy-based approach in stability estimation task also.

By analogy approach, according to terms of tensor analysis, description of processes and associated tensors in inverter-connected power sources are proposed. This result supplements tensor approach in electromagnetic systems analysis.

Future work will focus on building full mathematical model for stability estimation task. The first step is equations set-up, which are use tensor based approach.

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