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INNOVATIVE SCENARIO OF RUSSIAN POWER SECTOR DEVELOPMENT UP TO 2050

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Abstract. Changes in the technological base of world energy, scenerio of world energy development and innovative scenario of development power sector of Russia are being considered sequentially in the article. The final result of investigation is prognosis of dynamic consumption, export and production of electircal power sector in Russia, which is essential taking into account maximum of loading values of generating capasities with breaking them up according to the types of generation and also values of necessary input generating capasities taking into account output depreciated and outmoded equipment. On the basis of prognosis of electrical power engineering development the main directions of electrical power system development of Russia, network sector and control system are indicated and recommedations on foreground tasks of public policy in power industy are also formulated.

Keywords: Energy Development Scenarios, Power Sector, Technological Trends, Forecast of Electricity Consumption in Russia.

1. Introduction

Innovative scenario of Russian power sector development in association with innovative scenario of economics development and also in a context of technological trends of world electrical power engineering development are being considered in the present article. The analysis is being carried out on the basis of prognosises of Ministy of economic development and on the data of Energy strategy of Russia (ES-2030) giving more procise definitions of the period 2009-2012 in connection with the world crisis. For the period 2030-2050 original author appraisals were presented.The analysis of world technological and economical trends in electrical power engineering was carried out on the basis of complex prognosis of development world energy till 2050 which was performed in Energy Strategy Institute using scenario approach which allows to take into account complicated complex of energetic, technological, economical, social and policital factors.

2. Problem (theory)

Technological trends of world energy development.

Technologies of electric power generation. Technologies of electric power generation can be divided into 2 groups – developed technologies (for them it expects slugged development with some improvement of economic indicators) and developing technologies (for them it expects a quick progress of techno-economic indicators, implemententions of new technological solutions).

Technologies of gas, wind, bio and hydro power engineering and also thermal reactors in atomic power engineering are refered to developed technologies. In gas power engineering by 2030 capital expenditures on construction of combined-cycle plants with condensation cycle will decrease from modern level of 690 dol to 610 dol and by 2050 to 550 dol per kw. Efficiency can increase from 57% to 64%. *Terrestrial windmill*s has reached the stage of development. By 2030 capital expenditures on their construction can be decreased from modern level of 1500

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dol to 1200 dol, by 2050 - to 1000 dol per kw.[1] The technological progress is connected with growth of blades size, increasing energy conversion efficiency, control systems. The potential of reducing expenses on marine windmills is considerably higher. By 2030 capital expenditures on their construction can be reduced from modern level of 2900 dol to 1800 dol, by 2050 - to 1500 dol per kw. *Development of bioenergetic technologies* in perspective will be slowly. By 2050 capital expenditures on construction of condensation power plants on biomass will make nearly 2400 dol. The production of biogas requires additional capital investments but allows to use "inconvenient" kinds of stocks and worked out technologies of gas energy. *Hydroenergy* has reached the stage of development. More important role in modern system of electric power supply play micro HPP with capasity less than 1 MVt. Tidal and geothermal power plants apparently will play essential role only in local power systems. Currently in nuclear power engineering reactors on thermal neutrons of the second generation which were worked out in the 1970-1980s dominate (90% capasity). In perspective a gradual transition of world nuclear power engineering to the reactors of the 3rd and then to the 4th generation expects. The first reactors of the 3rd generation are being built (American-Japanese reactors AP-1000 - in China, european PWR- in Finland). The reactors of the 4th generation can be worked out in the 2010-2020s and its construction will be started from 2030.

Reactors on quick neutrons, new technologies of coal power engineering and also photo voltage are refered to technologies which are in the stage of development. *In carbon power engineering* implementention of integral complex of new thechnologies is expected. By 2030 efficiency of power units on coals can increase from 45% to 53%. Perspectives of coal sector technological development are connected with some directions: 1) power units with overcritical and superovercritical steam parametres 2) new methods of coal combustion (in boiling bed, in carbon dust, with internal cycle gasification) 3) with technologies of coal gasification 4) catch and disposal of carbon.

Thechnology of overcritical steam cycle (SCSC) is commercial. Half of all new stations in China are built on SCSC (in 2009 more than 60 GW). Power units with superovercritical parameters are not widespread yet because of their high price. New methods of coal combustion (in cycling boiling bed, in the form of carbon dust, with internal cycle gasification) are currently in the stage of experimental-industrial maintenance. After 2020 the main technology can be IGSS (integrated cycle of complex coal gasification). Technologies of catch and disposal of carbon (CCS) are focused only on reduction of waste CO_2. Currently some demonstration projects of CCS are working. Manufacturing technologies with CCS will appear only after 2020 and can be merchantable only after 2030. Manufacturing scheme is rather expensive therefore scale implementation of CCS will not occur (separate plants in Europe).

Low reliability and high prices of construction (20- 25% more expensive than usual reactors) are referred to one of the most important problems of existing *reactors on quick neutrons*. But their construction allows to use uranium - 228, which makes up 99.3% of natural resources while thermal reactors use only uranium - 235 (0.7% resources). Formation of reactors on quick neutrons is necessary in case of organization closed nuclear fuel cycle (CNFC). In 2009-2010 an interest to development of RBH dramatically increased. In Russia, which currently takes the leading position, BH-800 unit is built. Operations in this direction have begun or restarted in India, China, France, the Republic of Korea and Japan. In the frames of construction small nuclear electrical power plants in Russia, the first floating nuclear thermal power plant (FNTPP) with capacity 65 MVt intended for power service of remote districts of the Far North was launched in 2010 and in 2012 will begin its regular work.

[1]Assessment of capital expenditures in renewable power engineering was conducted according to Greenpeace data. Prognosis of this organization on dynamics of RES in retrospective ness show more validity as compared with other sources.

Development of photo voltage (direct conversion of solar energy into electric energy) in perspective will be rather quick. By 2030 capital expenditures on their construction can be decreased from modern level of 3700 dol to 1800 dol and by 2050 – to 1000 dollars per GW.

Indicated assessments come from optimistic estimation of manufacturing process; at a slow pace these indicators can be considerably higher. Irradiration rate (reduction of expenditure level at doubling capasity) for photo voltage during the last 35 years makes up 0,8. Maximum efficiency of solar voltaic arrays in 2008 reached 47% with mean values in used plants in 10-15%. Thin-film technology, multi node technology, semi conductive dyes are considered the most perspective technological variants.

In the 2000s especially intensive manufacturing process took part in renewable power engineering. For renewable energy sources (RES) in comparison with other types of generating capacities very low values of capacity factor (10-20%) are typical in comparison with nuclear power units (70-95%) and terminal power engineering (60-80%). In 2010- 2050 capacity factor of RES will increase as the result of optimization both operation of remote plants and power system in whole. The key problem is instability of wind and solar power engineering and mismatch of generation peaks with load peaks. This problem can be solved by developing energy storage system. Besides it will be getting easier in natural way as growth of scale of renewable power engineering and its geographical distribution.

Technological trends of electrical power systems development. Transition to power systems of a new generation will be fulfilled according to 4 directions: 1) creation of power system management ("smart power system") 2) development of distributed generation 3) development of electricity storage technologies in power system 4) development of distant transport power system technologies.

"Smart Grid" "Smart power system" is generalization of currently developed "smart grids" technologies and intends demand management for energy. Differential rates are used for this. In perspective power consumption equipment will be upgraded by electronic systems which allow to manage power consumption level on-line. Development of smart grids is profitable both for renewable power engineering which allows to adjust power consumption level under dynamics of electricity generation and for nuclear power engineering providing a big uniformity of loading. At the same time demand for maneuvering gas power and storage accumulation power plants will decrease. Distribution of electric vehicles will bring to alignment load duty on electrical power system because of consumption growth in night hours on recharging of accumulators which will allow to optimize mode of power system operation. Implementation of smart grids technologies will reduce losses in Russian power grids and cut down demand for new power and capital investments. In the USA and EU development of "smart grids" on civil level is considered the key goal in creation power engineering of future, and for appropriate systems development 30-50 billions a year are invested.

Distributed power engineering. Development of distributed generation supposes integration of power engineering into techno sphere. Trend of output energy expansion as by-product of other manufacturing processes including the use of waste energy resources has already formed. Development of RES in a context of "active house" and "active building" technologies allows to use potential of power production directly in buildings at the expense of solar power engineering, thermal power engineering, wastes, est. Development of distributed generation will bring to formation of "Virtual Power Plants" - groups of distributed electrical power generators which are under united control. In perspective integration of power consumer (industrial, service, communal) with producer will happen. The most potential of distributed generation development is concentrated in developed countries because of the high technological level and post-industrial type of economics. For this it is necessary to solve both technological problems (transition form asymmetrical nets to symmetrical where consumer and producer can change their places) and organizational (order of energy payment, order of power system management). This process will bring to partial transformation of energy market from goods market firstly to service and then to technology market.

Energy storage. Technologies of electricity storage in power system are necessary to increase effectiveness of capacities use and growth of power supply reliability. On the level of individual consumer, effective accumulators of high power can be a solution. However, the creation of such accumulators faces with real big difficulties than the creation of accumulators for electric vehicles, so on the level of energy system such solutions will not appear till 2030 (in case of technological break in the creation of superconductors their occurrence is possible by 2050). Technologies of energy storage will serve not for gross energy storage but for stabilization a mode of power system operation. Indirect ways of electric power storage on the level of power system can be implemented by means of creation hydroelectric pumped storage power plant.

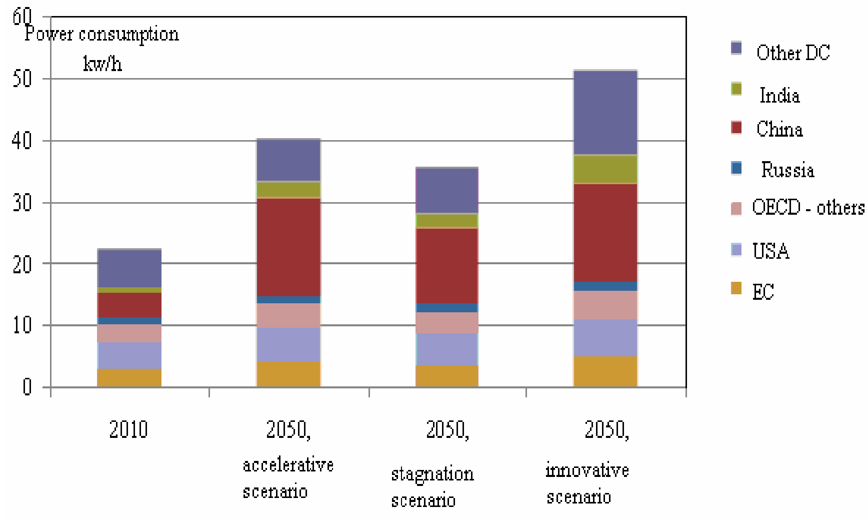
Electric power transmission systems. Complication of network topology demands concordance of phases and power control. Flexible transmission system on alternating current (FACTS) appeared nearly in 1990. In 1998 in the USA the first system UPFC (Unified system of energy steam control) that allowed to control active and reactive power was created. Such systems in the world are few so far. They are especially important in big cities with difficult network topologies. Technologies of power transmission line and insets of high voltage direct current (HVDC) and also using of superconductors are important for development of electric-power transmission. Direct current lines allow to increase capacity and connect the parts of alternating-current network with different phase and frequency. Reduction in value of superconducting equipment falls behind the forecast.

Taken as a whole pointed above trends come to the creation of intellectual power grids of new generation (UPS 2.0) with intellectual management from production to final consumption.

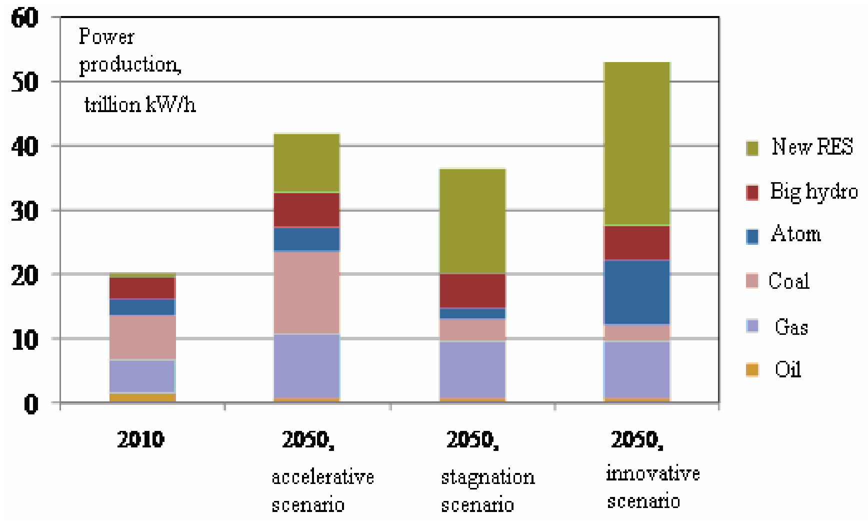
Scenarios of world power sector development

The trend analysis of world development indicates that there exist 3 different scenarios of world power sector development in the 2010-2050s: accelerative, stagnation and innovative. In all three scenarios world electrical energy consumption is increasing with leading speed in correlation to initial energy resources consumption on 78%, 56% and 126% accordingly by 2050 in comparison with 2030 (fig 1). In all 3 scenarios percent of developing countries is increasing from 49% in 2010 to 63%, 62% and 66% accordingly, at the same time the growth in developed countries continues too. The main quantitative trends in all 3 scenarios are the same. The fastest progress takes place in innovative scenario, the slowest - in stagnation. But the scenarios differentiate by qualitative characteristics of world energy development.

Accelerative scenario of world power sector development supposes to remain the dominate position of Thermal Power Plants. By 2030 power generation on coal plants will increase 2,05 fold and make 35.6% of total power generation, on gas power plants – 1,92 fold up to 23,7%, RES –5,54 fold up to 16,0% (fig. 2). RES, coal and gas generation will show maximum rates, but oil-firing – minimum. In accelerative scenario only separate elements of “smart grids” related to network and generation capacity management will be realized. Technologies of final electricity consumption control will not be used widely. Profile of load on electric power systems will remain rather uneven. The level of losses during electricity transportation will slightly reduce in comparison with modern level. As a result, growth of distance of electricity transportation will be enough only for optimization of present power systems (Europe, Russia, USA, China) but not for essential rearrangement of world power engineering. Power engineering in accelerative scenario will grow rapidly in magnitude relation and at the same time change relatively slowly in qualitative relation.



Note: DC- developing countries, OECD developed countries.
Source: calculations of Energy Strategy Institute.
Figure 1. Scenario of world energy development (regional aspect).



Source: calculations of Energy Strategy Institute.
Figure 2. Scenario of world energy development (sectoral aspect).

Stagnation scenario of world power sector development intends active energy saving, renaissance of nuclear and renewable power engineering to reduce CO waste. Power generation on gas plants by 2030 will increase 1.65 fold and make 29.0% of total power generation, RES power generation - 13,1 fold up to 26.0% (without hydropower engineering). At the same time power generation on nuclear plants will increase 18%, on coal plants will decrease 11% to 20.5%, on oil-fired plants 51% to 2.7%. In stagnation scenario the main elements of “smart grids’ will be realized. Technologies of profile of load control on power systems are spreading. To integrate unstable energy sources (RES, distributed generation) in power system indirect ways of electric power storage at the level of energy systems by means of creating hydroelectric pumped storage power plants, accumulators of different types will be used. After 2030 it is possible to use a manufacturing scheme with hydrogen production as energy storage due to NPP electricity and tidal PS.

Innovative scenario of world power sector development.

Nuclear and renewable power engineering will play the decisive role in dynamics of power engineering. RES power production will increase 16-fold up to 26.7% of total production by

2030, and by 2050- to 48%. Nuclear generation will increase 4-fold by 2030, and its share will reach 20%. Intellectual unified power systems of new generation will come into existence. Technologies of “smart grids” will be realized in large scale. The level of losses during electricity transportation will reduce in comparison with modern level due to development of direct current and use of superconductors technology. Radical enhancement of electricity transportation will bring to formation of unified power systems of Europe, Eastern Asia, Northern America, Russia and neighboring countries by 2030, and also connections between them. In perspective 2050, indicated trend will bring to formation of Unified Power system base of Eurasia. Opportunities to use electricity in all types of power plants which according to ecological (Nuclear power plants and large scale coal TPP) reasons are preferable to place in under-populated districts or based on resources concentrated in under-populated districts (some Hydropower plants and coal TPP, part of RES – wind and solar power plants) are increasing. Development of international electricity trade requires solving not only technical, but also organizational (order of dispatching), economical (world markets production) and political problems. The level of mutual confidence of the countries connected with supply of electricity must be rather high.

Scenario of power engineering development of Russia.

Scenario of power engineering development of Russia is based on the one hand on above mentioned world tends of industry development and on the other hand on scenario of economical development of Russia taking into account internal tends and factors of the industry development.

Scenario of economical development of Russia. Innovative scenario of power engineering development is based on innovative scenario of economics development. Only on the base of innovative scenario long-term growth rates of GDP more than 4% a year, structural rearrangement of economics, approaching with developed countries at the level of economic development can be provided. Potential of export-raw models of economic growth is close to exhaustion. It is time to change the leader of growth in Russian economics and access to the leading position of highly technological industries. A whole complex of reforms concerned public administration, budget, industrial and technological policy is required for this. In the frames of innovative scenario accepted growth rates of GDP in Russia provide growth of this rate in Russia 3, 7-3, 8 fold by 2030 and by 2050 6.5 – 7.5 fold in comparison with 2007 level and take into account high potential availability of innovative transformation of economics of Russia (table1)

Table 1.Innovative scenario of development economics and power sector of Russia.

Year	2010	2020	2030	2040	2050
GDP, % to the level of 2005	114,2	221	367	600,0	971,0
Average annual growth rate of GDP, %	3,5	6,2	4,8	5,0	5,0
Electro capacity of GDP, % to the level of 2005	91,7	71	61	48,0	36,0
Dynamics of specific electro capacity , % a year	0,0	-2,6	-2,1	-2,8	-3,0
Average annual increase of demand for electricity, %	2,4	2,7	2,1	2,2	2,9
Demand for electricity in Russia, billion. kw	1012	1315	1740	2227	2669
Export of electricity, billion. kW/h	13	35	60	90	120
Electricity production, billion, kW/h	1025	1350	1800	2317	2789
HPP	690	873	1098	1353	1618
NPP	165	247	356	494	654
HPP	170	224	319	370	410
Required installed capacity of power plants, kw	224	275	355	435	534
European part of Russia	130,5	160,4	207,0	254,2	308,8

Ural	29,2	35,8	46,0	55,6	64,8
Siberia	50,0	61,4	79,5	98,2	123,2
The Far East	14,1	16.4	22,5	27,0	37,2
TPP	154	172,0	212,0	255,0	302,0
NPP	23,2	37,0	52,0	72,0	92,0
HPP	46,8	62,0	83,0	90,0	100,0
RES	0,1	4	8	18	40
Required capacity input of plants, Gw		108,8	183,7	148	160
NPP - output		0	6,7	5	5
NPP- input		13,7	21,7	25	25
HPP - output		0	0	0	0
HPP- input		15,2	31	9	15
TPP - output		17,8	48	40	35
TPP- input		35,8	88	83	92
RES- input		4	4	10	22

Sources: The 2005-2009s - fact; 2010 - assessment, the 2015 -2050s - forecast the 2015-2030s in accordance with PS - 2030 and assessments of Energy Strategy Institute.

Dynamics of electricity consumption in Russia. Assessment of dynamics of specific electro capacity of economics of Russia for the period to 2050 and demand for electricity within the country indicates that for the 2011- 2030s growth of GDP production of Russia 3.3 fold up by decreasing specific electro capacity of economics to 36% and increasing demand for electricity 1.74 fold up is forecasted. Over the 2031 - 2050s GDP of Russia will increase 2.7 fold up, specific electro capacity will decrease to 41% and demand for electricity will increase 1.5 fold up. In perspective the 2010-2050s, further growth of demand for electricity in Russia should be expected. Because of structural transformations of economics and development of power supply growth rate of demand for electricity for the period of the 2030-2050s will be lower than retrospective ones (without taking into account the crisis of 2008-2010) and lower than in 2010-2030 according to PS -2030 (on average 2-2.1% a year instead of 2.5-3.7% for the period of 2001-2009). So innovative scenario of economics development due to high increase of power efficiency (including both energy saving and increase of final product formed during using electricity) provides moderate power consumption at rapid growth of economics.

Dynamics of required installed capacity of power plants. Calculating required capacities besides covering internal demand (including load peaks) and also electricity export, required capacity reserve, limits of using capacities are taken into account. A number of hours using maximum load in Russia in 2009 made 6300 hours a year. Load peak made 150kv. Less under populated are schedules of electric loads in European part of the country and in Ural, more populated - in Siberia. Average annual use of maximum loads in the period under review will not change considerably. Values of rated calculated power reserve on IPS and IPG of Russia are determined in accordance with methodological recommendations on power system development design and makes 12-22% from maximum of load. Limitations of power plants capacity due to networks possibilities make to 10% from the installed capacity. The structure of power generation is transferred mainly to the side growth of NPP from 15.8% in 2007 up to 22.5% in 2050 with some decrease of TPP share (from 66.6% to 62-63%) and also HPP and so on (from 17.6% to 14-16%) The volume of power generation on power plants that don't use organic fuel is increasing from 340 billion kW/h in 2007 to 1055 billions kW/h.

In the area of the thermal power plants on gas fuel, combined-cycle modular plants of unit capacity from 70 to 750-800 MVt with efficiency accordingly from 52-53% to 55-60% equipped with reservation system of fuel supply will prevail. Gas Turbine Power Plants and combination of Gas Turbine power plants with exhaust-heat boiler for electricity and heat production will be used widely for purposes of regulation. Generating capacities on coal will present installations on overcritical and supercritical parameters of stream with efficiency from 46 to 55% (in case of quantitative high-caloric coal), installations with boilers with circulation boiling bed, with boilers with "low temperature vortex" and also installations with coal gasification and energotechnological installations will be developed. Total average efficiency of power generation on coal will make 41%. These innovative transformations will bring to reduction of specific fuel consumption on electricity release from 330 gram of reference fuel by 1 kW/h at present to 270 - in 2030 and to 250 - in 2050 accordingly.

In nuclear power engineering by 2030 in European part of Russia serial units of NPP with water-moderated water-cooled reactor (VVER) of 1000-1500 mw capacities with efficiency to 36% and capacity factor to 90% on uranium and uranium-plutonium fuel in closed nuclear fuel cycle will prevail. After 2030 more shares in NPP structure will take reactors on quick neutrons. On the periphery of IPG of Russia and in isolated energy nodes energy units of NPP and NTPP with VVER reactors of average capacity (to 600 MVt) of increased safety will be used.

In close regions of The Far North and the Far East for energy supply of isolated consumers floating energy units with nuclear thermo power plants with small capacity to 70 MVt will be spread.

RES power production will be connected with geography of economically effective potential appreciate initial energy sources including solar and bio energy especially in the southern regions of the country; wind - in zones of stable winds with the speed more than 8 - 10 m/sec, including on the Far East, on the North of the country, in the region of Novorossiysk etc, geothermal - in the regions of Far East, the Ciscaucasian area, in South-Western Siberia etc; tidal - in the regions with big range of tidal sea level (the Far East, the Far North); low-potential heat - everywhere.

In European part of the country the development of primary power NPP as compared with TPP working on exported natural gas has priority. It requires serial construction of NPP with reactors on quick neutrons and complexes for secondary nuclear fuel reprocessing and also the development of works on exploration resources and gas natural uranium output. The development of TPP on natural fuel in these regions must be fulfilled on gas in additional to NPP in base mode and in semi peak modes with construction of stream gas power units both on new TPP and instead of steam power plants. In order to satisfy consumption in peak capacities along with using HPP and HPSPP, a construction of gas turbo-generator set is considered.

On Ural and in Siberia the perspective of TPP development is focused on coals of Kuzbass, Transbaikalia. TPP of the Far Eastern federal district except separated urban TPPs will also use coal fuel, for their fuel supply is intended to use Sakhalin and Yakut gas. In Siberian and Far Eastern regions which are rich in water resources, development of hydro power engineering especially in semi peak and peak type of energy source will go on. Competitiveness of NPP in Siberia and on the Far East under the conditions large sources of cheap coal availability and perceptiveness of new gas fields are unlikely.

Required capacity input of power plants. Despite of decline of growth rate of demand for electricity, a necessity to launch new power engineering capacities dramatically increases which is connected with twenty years' failure of investment in industry and inevitable outflow of worn-out units. 56% of all power plants have already been operating for more than 30 years. As a result at average annual input of new capacities for the period of the 1992-2009s less 2 GW is required to bring to 7 GW in the 2011-2020s taking into account replacement of worn out capacities, in the 2021-2030s to 14 GW a year and in the 2031-2040s to 13 GW. Sizes of required input of capacities for secure power supply of the country at the forecasting rates of its economical development are very high, especially in the period of the 2021-2030s when at the same time peak retirement of old capacity appears and high growth rate of economics and demand for electricity are forecasted. In that period average annual volumes of required inputs of capacities are unprecedented and exceed by 1, 5 of volume inputs in the best period of USSR engineering. The solution of this task requires drawing up state program of input implementation of new energy capacities in the county as present situation is a threat to energy security of the country.

Development of Integrated Power System of Russia and electric networks. In the 2010 - 2050s in Russia under influence of world technological trends, a formation of unified power system of new generation on the basis of “smart grids” technologies with renewable power engineering development which will allow radically to increase economics and power engineering efficiency is expecting. The basic principle of strategy of development unified power system of Russia provides that connected power grids to 2050 are being constructed mainly as balanced according to production and power consumption. Electricity exchange between them is being carried out to realize advantages of power system cooperation and concern mainly peak loads. The main electricity transit will be conducted in the direction Siberia - Ural - European part of Russia. Control devices (controlled shunt reactors, thyristor static compensators, lengthwise capacitive compensation, unified regulators of power flow, rotary devices, STATCOMs, asynchronous communication interface adapter - transmission and back-to-back the DC, electromechanical transformation, electric energy storage) and new highly effective control systems of electric networks will be used widely. Superconductor devices mainly cables, accumulators, current-limiting devices will be used. Total power engineering market of CIS countries and total market power engineering space with PS and other countries on Eurasian continent will be created.

3. Conclusions

In the 2010-2030s and especially in the 2030-2050s the world power engineering will undergo radical changes. Firstly, structure of generating capacities due to rapid growth of renewable power and rapid progress of appropriate technologies will change. Secondly, principles of organization of power systems due to transfer to ”smart engineering” and formation of power system of new generation will radically change. The dynamics of Russian electricity will have to conform to new technological trends and tasks of reliable power supply of the country. There are significant risks of quantity loss of capacity and quality lags of Russian power engineering from the other countries. In order to solve these problems the integral strategy of industry development is required.

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PARALLEL OPERATION OF WIND POWER FARM WITH DOUBLE FED INDUCTION GENERATORS WITH ELECTRIC POWER SYSTEM

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ABSTRACT. The method of mathematical modeling of power system is being carried out jointly operating with wind power plants which contain Double Fed Induction Generator (DFIG) used as generators. The main point and the advantage of the method is that it allows to "match" the equation of double fed induction generator effectively which are recorded in the rotating axes with the speed of rotor machine with the equations of the external power network recorded in synchronously rotating axes.

Keywords: Wind Power Plants, Wind Power Farm, Double Fed Induction Generator, Current Frequency, Rotational Frequency, Moment-power Characteristic.

1. Introduction

Wind power farm (WPF), equipped with double fed induction generator (DFIG), used as generators, is a dominant majority. Suffice it to mention the producing well-known firms: Vestas, Camesa, etc. They provide more than 75% of power production of the world wind-power engineering branch, which total amount at the beginning of 2010 constituted 160 GW.

Since the modern wind power units, along with thermal, hydro and nuclear power plants became an integral structure of electric power system, the issues of modeling of complex electric power system, based on the synchronous machines, operated in conjunction with double fed induction generator, used as WPPs' generators, are of interest.

Let's consider the shown in fig. 1 electric power transmission circuit, in which the wind power farm (WPF) with generators based on the DFIG, has a local load center and is connected via high-voltage transmission line with receiving buses system of infinite capacity.

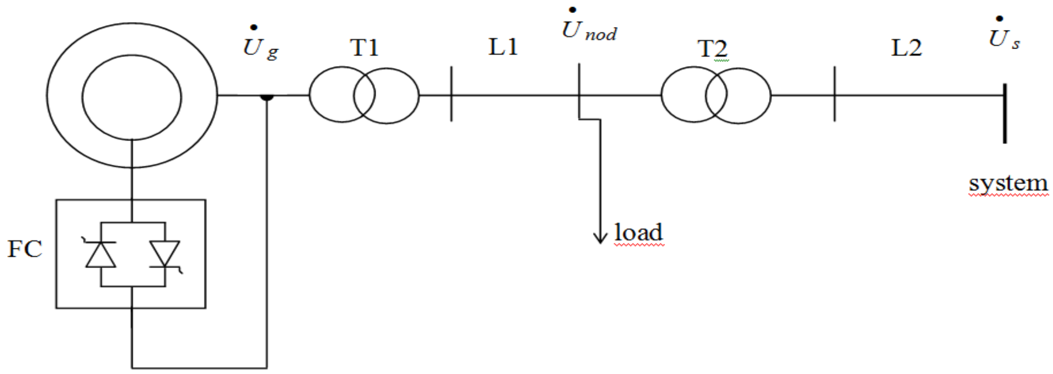

Figure 1. Electric power transmission circuit of wind power farm.

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2. Research and a method for modeling equations of AMDP, "aligning " equations with an external network

Here the WPF's generator is DFIG, which rotor winding is fed from the stator side via a frequency converter FC (carried out in most cases on completely controlled IGBT - transistors). Output voltage of generators of modern WPPs is either 0,69 kV or 0,66 kV (rarely 1 kV). T1 transformer, which supples each WPP, converts the generator's voltage, as a rule, to 20 kV (or 10, 35 kV on request). From the output buses of T1 transformer the WPP's power through L1 line is delivered to the busbars system, from which a part of power can be taken to a local load, and the other one is transmitted to the power system via T2 transformer and L2 transmission line. T2 transformer, conducted a connection of WPF with power system, converts a voltage from 20 kV to 154 kV or 220 kV (or 110 kV) (fig. 1).

Of course, the above circuit can not be the only one, but it is the most common, so it can be considered, as the basic one (standard). On equivalent circuit the parameters of T1 transformer and L1 line are integrated, as well as the parameters of T2 transformer and L2, and the load is presented by constant conductance shunts g_n and b_n.

Thus, the purpose of research is to create a modeling technique, which would be the most appropriate way to make for "aligning" of DFIG equations with the equations of external network.

The equations for WPP's DFIG [1,2] are presented in rotating with rotor speed d, q axes. It was demonstrated, that it was an expedient form of DFIG mathematical model presentation, as it allowed relatively easy to change (manage) the DFIG control parameters – frequency of current in its rotor windings and voltage amplitude (as well as the excitation current in the synchronous machine).

However, the "aligning" of the WPP's DFIG equations, written in rotating with rotor speed d, q axes, directly with shown in fig.1 the power system elements is impossible, because i_d, i_q currents and $U_d = -U_s \cdot sin\theta$ and $U_q = U_s \cdot cos\theta$ voltages of DFIG at steady–state mode are the variables, changing with a frequency of slip.

Let's demonstrate this by specific example. DFIG equations are presented in the form:

$$\left.\begin{array}{l}
p\Psi_{ds} = -U_s \cdot sin\theta + \psi_{qs} \cdot (1-s) - r_s \cdot i_{ds} \\
p\Psi_{qs} = U_s \cdot cos\theta - \psi_{ds} \cdot (1-s) - r_s \cdot i_{qs} \\
p\psi_{dr} = -U_s \cdot k_{ur} \cdot sin\left(k_{fr} \cdot \tau\right) - r_r \cdot i_{ds} \\
p\psi_{qr} = U_s \cdot k_{ur} \cdot cos\left(k_{fr} \cdot \tau\right) - r_r \cdot i_{qs} \\
ps = -\frac{1}{T_j} \cdot m_{\mathrm{WM}} - \frac{1}{T_j} \cdot m_{\mathrm{EM}} \\
p\theta = s \\
m_{\mathrm{EM}} = \psi_{ds} \cdot i_{qs} - \psi_{qs} \cdot i_{ds} \\
i_{ds} = k_s \cdot \psi_{ds} - k_m \cdot \psi_{dr} \\
i_{qs} = k_s \cdot \psi_{qs} - k_m \cdot \psi_{qr} \\
i_{dr} = k_r \cdot \psi_{dr} - k_m \cdot \psi_{ds} \\
i_{qr} = k_r \cdot \psi_{qr} - k_m \cdot \psi_{qs}
\end{array}\right\} \tag{1}$$

where $k_s = \frac{x_r}{x_r \cdot x_s - x_m^2}$; $k_r = \frac{x_s}{x_r \cdot x_s - x_m^2}$; $k_m = \frac{x_m}{x_r \cdot x_s - x_m^2}$.
x_s – full inductances of stator and rotor circuits and mutual induction inductance;
U_s – module of stator circuit voltage;
k_{ur} – factor, which takes into account the transformation of stator voltage U_s into the rotor one;
k_{fr} – frequency of current in rotor windings, proportional to a set value of s slip;
r_s, r_r – resistances of stator and rotor circuits;
$\tau = 314 \cdot t$ – synchronous time.

Parameters of model generator on the basis of DFIG :

$$\mathrm{r}_s = 0,0115; \mathrm{r_r} = 0,0122; \mathrm{x}_s = 3,126; \mathrm{x}_m = 3,021; \mathrm{x_r} = 3,13; \ \frac{1}{T_j} = 0,03.$$

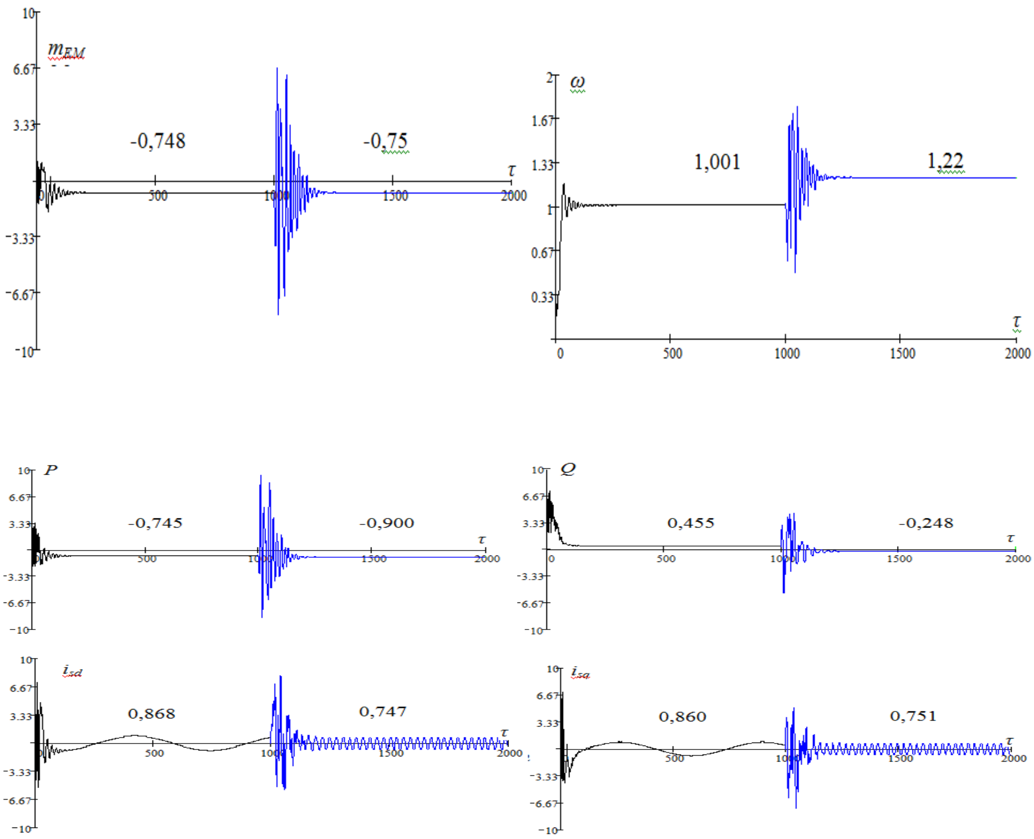
For $U_s = 1$, $k_{ur} = 0{,}23$, $k_{fr} = 0{,}22$ DFIG rotational frequency can exceed the synchronous one by 0,22, i.e. becomes equal to $\omega_r = 1{,}22$, and can be lower it by $\Delta\omega = 0{,}22$, i.e. becomes equal to ω_r=0,78. In the second case the signs before rotor circuits voltage components are the same, as it is shown in above equations. In order to operate in a mode with $\omega_r = 1{,}22$, it is necessary in the fourth equation of above system to change a sign before $U_s \cdot k_{ur} \cdot \cos(k_{fr} \cdot \tau)$ component from positive to negative one.

Besides that the active power equations of stator – P_s and rotor – P_r and reactive power equations of stator – Q_s and rotor – Q_r must be added to equations (1), which are determined by the following relations:

$$\left.\begin{array}{l}
P_s = -U_s \cdot \sin\theta \cdot i_{ds} + U_s \cdot \cos\theta \cdot i_{qs} \\
P_r = -U_s \cdot k_{ur} \cdot \sin(k_{fr} \cdot \tau) \cdot i_{dr} \pm U_r \cdot k_{ur} \cdot \cos(k_{fr} \cdot \tau)_s \cdot i_{qr} \\
Q_s = U_s \cdot \cos\theta \cdot i_{ds} - (-U_s \cdot \sin\theta) \cdot i_{qs} \\
Q_r = \pm U_s \cdot k_{ur} \cdot \cos(k_{fr} \cdot \tau) \cdot i_{dr} \pm U_r \cdot k_{ur} \cdot \sin(k_{fr} \cdot \tau)_s \cdot i_{qr} \\
P = P_s + P_r \\
Q = Q_s + Q_r
\end{array}\right\} \quad (2)$$

Sign "+" corresponds to ω_r=0,78 mode, and a sign "-" to ω_r=1,22 mode.

The fluktogramms, showing the changes of mode parameters of model generator for given above the values of its resistances and inductances, which correspond to operating mode higher than synchronous rotational frequency with ω_r=1,22 (i.e. for value of current frequency in rotor windings equal to k_{fr}=0,22) are presented in fig.2. For all this k_{ur}=0,23, and torque, developed by wind motor, is $m_{EM} = -0,75$, that roughly corresponds to calculated wind speed V_{calc}, for which the output to network power is equal to rated one.



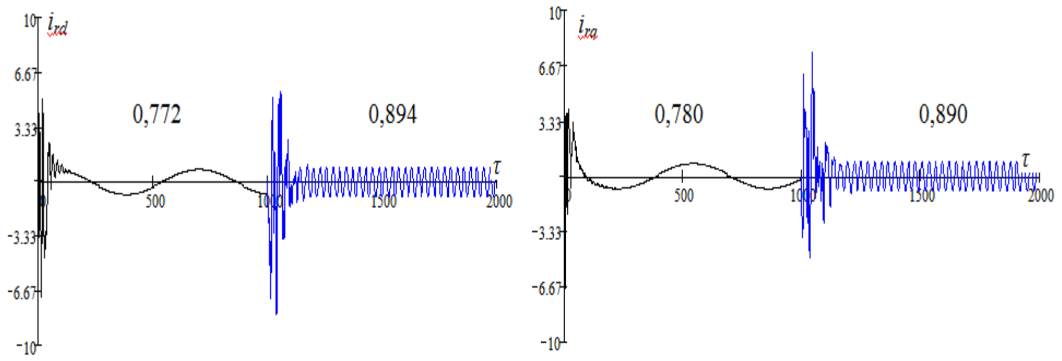


Figure 2. The changes of mode parameters of model generator for given above the values ??of its resistances and inductances.

For all this WPP's DFIG is connected directly to network of infinite capacity with $U_d = -1 \cdot \sin\theta$, $U_q = 1 \cdot \cos\theta$ with driving torque on the shaft equal to m_{WM}, i.e. DFIG accelerated in traction mode, then it goes to generator mode – in this case rotor winding was short-circuited, at 1000th radian a voltage of corresponding amplitude and equal to slip frequency was applied to rotor winding.

It is seen from the analysis of fluktogramm, for writing the equations in d, q axes, rotating with DFIG rotor speed, stator and rotor currents have equal to slip frequency for ω_r=1,22, frequency k_{fr}=s=–0,22; (and for ω_r=0,78 it will be k_{fr}=s= +0,22). For all this the components of stator and rotor currents i_{ds}, as it should be, are almost equal to each other: for ω_r=1,22 and $m_{\mathrm{WM}} = -0,75$ (and for ω_r=0,78 and $m_{\mathrm{W}M} = -0,35$). Being the scalar quantities the active and reactive powers are trained by equations (2). The power factor for ω_r=1,22 is cosφ≈0,95 (advancing), and for ω_r=0,78 cosφ≈0,9 (lagging).

The essence of proposed in this paper modeling lies in the fact, that the equations of external network from the generator's terminals with $\dot{U}_g$ to buses of infinite capacity $\dot{U}_s$ are written under the assumption, that the axes of complex plane are aligned with d_0, q_0 axes, rotating with a constant synchronous speed under the condition, that q_0 axis coincides with the axis of real numbers. Further, these equations of external network, were already laid out along d_0, q_0 axes, are jointly solved. And in the end, by transition from recorded in d_0, q_0 axes the voltage and current components to components of d, q axes of DFIG, the values of DFIG voltage components U_d and U_q are synthesized, which take into account the parameters of the external network and the components of i_d, i_q currents of DFIG.

Integrating the parameters of T1transformer and L1 first line we will write the equation of voltages balance for this section from generator's buses $\dot{U}_g$ to buses of node $\dot{U}_{nod}$:

$$\dot{U}_g = \dot{U}_{nod} + \dot{I}_g \left(r_{{}_{LT1}} + jE_{{}_{LT1}}\right) \tag{3}$$

where $\dot{I}_g$ – DFIG's current complex, $r_{{}_{LT1}}$ and $x_{{}_{LT1}}$– total resistances and inductances of T1 transformer and L1 line.

The equations of load, when modeling it by shunts of constant conductivity g_n, b_n [2], can be written as:

$$\dot{I}_n = \dot{U}_{nod} \cdot (g_n + j\, b_n)\,. \tag{4}$$

The equation of L2 second line (also aligning the parameters of L2 and T2) will be:

$$\dot{U}_{nod} = \underset{s}{\dot{U}} + \dot{I}_L \left(r_{{}_{LT2}} + jE_{{}_{LT2}}\right), \tag{5}$$

where $\dot{U}_s$ – voltage of the receiving system; r_{LT2} and x_{LT2} – total resistances and inductances of T2 transformer and L2 line; $\dot{I}_L$ – current in L2 second line.

And finally, the currents balance equation:

$$\dot{I}_n = \dot{I}_g - \dot{I}_L\,. \tag{6}$$

As it was noted, aligning the axis of real numbers with q_0 axis, and the axis of imaginary numbers with d_0 axis, we will obtain for (3) – (6) equations the following equation on q_0è d_0 components:

L1, T1:
$$\left.\begin{aligned} U_{gq_0} &= U_{nod.q_0} + r_{LT1}\cdot i_{gd_0} - x_{LT1}\cdot i_{gq_0} \\ U_{gd_0} &= U_{nod.q_0} + x_{LT1}\cdot i_{gq_0} + r_{LT1}\cdot i_{gd_0} \end{aligned}\right\} \tag{7}$$

Load:
$$\left.\begin{aligned} i_{nq_0} &= g_n U_{nod.q_0} - b_n\cdot U_{nod.d_0} \\ i_{nd_0} &= b_n U_{nod.q_0} + g_n\cdot U_{nod.d_0} \end{aligned}\right\} \tag{8}$$

L2, T2:
$$\left.\begin{aligned} U_{nod.q_0} &= U_{sq_0} + r_{LT2}\cdot i_{Lq_0} - x_{LT2}\cdot i_{Ld_0} \\ U_{nod.d_0} &= U_{sd_0} + x_{LT2}\cdot i_{Lq_0} + r_{LT2}\cdot i_{Ld_0} \end{aligned}\right\} \tag{9}$$

Current balance:
$$\left.\begin{aligned} i_{nq_0} &= i_{gq_0} - i_{Lq_0} \\ i_{nd_0} &= i_{gd_0} - i_{Ld_0} \end{aligned}\right\} \tag{10}$$

After numerous substitutions and transformations we will obtain an expression for voltage components on generator's terminals in q_0 and d_0 axes in the form of:

$$\left.\begin{aligned} U_{gq_0} &= k_{uq}\cdot U_{sq_0} + k_{ud}\cdot U_{gd_0} + k_{iq}\cdot i_{gq_0} - k_{id}\cdot i_{gd_0} \\ U_{gd_0} &= k_{uq}\cdot U_{sd_0} - k_{ud}\cdot U_{gq_0} + k_{id}\cdot i_{gq_0} + k_{iq}\cdot i_{gd_0} \end{aligned}\right\} \tag{11}$$

where $k_{uq} = \frac{1}{1+r_{LT2}\cdot g_n - x_{LT2}\cdot b_n}$; $k_{ud} = \frac{r_{LT2}\cdot b_n + x_{LT2}\cdot g_n}{1+r_{LT2}\cdot g_n - x_{LT2}\cdot b_n}$

$$k_{iq} = \frac{r_{LT1} + r_{LT2} + (r_{LT1}\cdot r_{LT2} - x_{LT1}\cdot x_{LT2})\cdot g_n - (r_{LT1}\cdot x_{LT2} + r_{LT2}\cdot x_{LT1})\cdot b_n}{1 + r_{LT2}\cdot g_n - x_{LT2}\cdot b_n};$$

$$k_{id} = \frac{x_{LT1} + x_{LT2} + (r_{LT1}\cdot x_{LT2} + r_{LT2}\cdot x_{LT1})\cdot g_n + (r_{LT1}\cdot r_{LT2} - x_{LT1}\cdot x_{LT2})\cdot b_n}{1 + r_{LT2}\cdot g_n - x_{LT2}\cdot b_n}.$$

Further, if to write the equations (11) only relatively the voltage components of infinite capacity buses and currents, we will get:

$$\left.\begin{aligned} U_{gq_0} &= \frac{k_{uq}}{k_{dq}}\cdot U_{sq_0} + \frac{k_{ud}\cdot k_{uq}}{k_{dq}}\cdot U_{sd_0} + \frac{k_{iq}+k_{ud}\cdot k_{id}}{k_{dq}}\cdot i_{gq_0} - \frac{k_{id}-k_{ud}\cdot k_{iq}}{k_{dq}}\cdot i_{gd_0} \\ U_{gd_0} &= \frac{k_{uq}}{k_{dq}}\cdot U_{sd_0} - \frac{k_{ud}\cdot k_{uq}}{k_{dq}}\cdot U_{sq_0} + \frac{k_{iq}-k_{ud}\cdot k_{iq}}{k_{dq}}\cdot i_{gq_0} + \frac{k_{iq}+k_{ud}\cdot k_{id}}{k_{dq}}\cdot i_{gd_0} \end{aligned}\right\} \tag{12}$$

where $k_{dq} = 1 + k_{ud}^2$

And finally, proceeding from the recorded in synchronous rotating d_0, q_0 axes parameters to the parameters in d, q axes, rotating with DFIG's rotor speed by well–known relations for currents:

$$\left.\begin{aligned} i_{gq_0} &= -i_{gd}\cdot sin\theta + i_{gq}\cdot cos\theta \\ i_{gd_0} &= i_{gd}\cdot cos\theta + i_{gq}\cdot sin\theta \end{aligned}\right\} \tag{13}$$

and for voltages:

$$\left.\begin{aligned} U_{gq} &= U_{gd_0}\cdot sin\theta + U_{gq_0}\cdot cos\theta \\ U_{gd} &= U_{gd_0}\cdot cos\theta - U_{gq_0}\cdot sin\theta \end{aligned}\right\} \tag{14}$$

Finally, we will get:

$$\left.\begin{aligned} U_{gq} &= (k_1\cdot U_{sd_0} - k_2\cdot U_{sq_0})\cdot sin\theta + (k_1\cdot U_{sq_0} + k_2\cdot U_{sd_0})\cdot cos\theta + k_3\cdot i_{gq} - k_4\cdot i_{gd} \\ U_{gd} &= (k_1\cdot U_{sd_0} - k_2\cdot U_{sq_0})\cdot cos\theta - (k_1\cdot U_{sq_0} + k_2\cdot U_{sd_0})\cdot sin\theta + k_4\cdot i_{gq} + k_3\cdot i_{gd} \end{aligned}\right\} \tag{15}$$

where $\mathrm{k}_1 = \frac{\mathrm{k_{uq}}}{\mathrm{k}_{dq}}$; $\mathrm{k}_2 = \frac{\mathrm{k}_{\mathrm{u}d}\cdot\mathrm{k_{uq}}}{\mathrm{k}_{dq}}$; $\mathrm{k}_3 = \frac{\mathrm{k_{i}}_q+\mathrm{k}_{\mathrm{u}d}\cdot\mathrm{k_{i}}_d}{\mathrm{k}_{dq}}$; $\mathrm{k}_4 = \frac{\mathrm{k_{i}}_d-\mathrm{k}_{\mathrm{u}d}\cdot\mathrm{k_{i}}_q}{\mathrm{k}_{dq}}$.

With this in mind, the first four equations of WPP's generator can be rewritten as:

$$\left.\begin{array}{l} p\Psi_{ds} = U_{\mathrm{g}d} - \omega_r \cdot \psi_{qs} - r_s \cdot i_{ds} \\ p\Psi_{qs} = U_{\mathrm{g}q} + \omega_r \cdot \psi_{ds} - r_s \cdot i_{qs} \\ p\psi_{dr} = -U_{\mathrm{g}} \cdot k_{ur} \cdot sin\left(k_{fr} \cdot \tau\right) - r_r \cdot i_{dr} \\ p\psi_{qr} = \pm U_{\mathrm{g}} \cdot k_{ur} \cdot cos\left(k_{fr} \cdot \tau\right) - r_r \cdot i_{qr}. \end{array}\right\} \tag{16}$$

Where voltage components $U_{\mathrm{g}d}$ and U_{gq} are defined by relation (15), and a voltage module on generator terminals is:

$$U_{\mathrm{g}} = \sqrt{U_{\mathrm{g}d}^2 + U_{\mathrm{g}q}^2}. \tag{17}$$

When forming the voltage components U_{g} (15) it needs to pay attention to the following circumstance. Included in them expressions for the components of generator currents i_{gd}, i_{gq} according to the circuit in fig. 1 shall be determined by the following expressions.

$$\left.\begin{array}{l} i_{\mathrm{g}d} = i_{\mathrm{ds}} + k_{\mathrm{ur}} \cdot i_{dr} \\ i_{\mathrm{gq}} = i_{\mathrm{qs}} + k_{\mathrm{ur}} \cdot i_{qr} \end{array}\right\}. \tag{18}$$

The rest of the system equations remain unchanged, except the expressions for powers, which are written as:

$$\left.\begin{array}{l} P_s = U_{\mathrm{gd}} \cdot i_{ds} + U_{\mathrm{gq}} \cdot i_{qs} \\ P_r = -U_{\mathrm{g}} \cdot k_{ur} \cdot sin\left(k_{fr} \cdot \tau\right) \cdot i_{dr} \pm U_{\mathrm{g}} \cdot k_{ur} \cdot cos\left(k_{fr} \cdot \tau\right) \cdot i_{qr} \\ Q_s = U_{\mathrm{gq}} \cdot i_{ds} - U_{\mathrm{gd}} \cdot i_{qs} \\ Q_r = \pm U_{\mathrm{g}} \cdot k_{ur} \cdot cos\left(k_{fr} \cdot \tau\right) \cdot i_{dr} + U_{\mathrm{g}} \cdot k_{ur} \cdot sin\left(k_{fr} \cdot \tau\right) \cdot i_{qr} \end{array}\right\} \tag{19}$$

$$P_{\mathrm{g}} = P_s + P_r; Q_{\mathrm{g}} = Q_s + Q_r.$$

In expressions (16) – (19) sign (±) in front of U_{g} with the cosine component means, that when controlling a generator rotational frequency above a synchronous one, it needs to use (–) sign, and below the synchronous one (+) sign.

In [3] it is offered to consider a moment-power characteristic in 4 zones. When operating in power system, the WPP operating mode under normal load, corresponded to the calculated wind speed, is of interest, for all this for WPP with DFIG the generator's rotational frequency tops the synchronous one by 20–30%, and in this case $\cos\varphi_3 \approx 0,9 \div 0,92$ (advancing), and operating mode is at minimum load, when the generator's rotational frequency is by 20–30% lower than synchronous one, for all this $\cos\varphi_{\mathrm{g}} \approx 0,88 \div 0,9$ (lagging). In the first case DFIG returns active and reactive power to the network, while in the second case it returns the active power to the network and consumes the reactive one.

Table 1.Operating parameters of the system in rotating with synchronous speed d_0 and q_0 axes for their steady-state values is compiled

	ω_r=1,22, k_{ur}=0,23	ω_r=0,78,k_{ur}=0,23
U_{sq_0}	1	1
U_{sd_0}	0	0
i_{gq_0}	–0,554	–0,255
i_{gd_0}	0,0357	0,152
i_{nq_0}	0,42	0,409
i_{nd_0}	0,58	0,587
i_{Lq_0}	–0,13	0,15
i_{Ld_0}	0,61	0,74
$U_{nod.q_0}$	1,02	1,019
$U_{nod.d_0}$	–0,0547	–0,0377
U_{gq_0}	1,018	1,01
U_{gd_0}	–0,082	–0,049
U_{rd_0}	1,021	1,0117

Thus, with taking into account the external network parameters, adduced and calculated according to relevant relations of Appendix (case 1), the stated below table of operating parameters of the system in rotating with synchronous speed d_0 and q_0 axes for their steady–state values is compiled. The calculation of these parameters of the system have been carried out for voltage components values of buses of infinite capacity equal to $U_{sq_0} = 1$ and $U_{sd_0} = 0$. The values of generator's voltage components in d, q axes U_{gd}, and U_{gq}– rotating with DFIG's rotor speed have been formed by the equations (15).

In the first column of the table the values of system operating parameters are reflected when working of WPP with DFIG in the mode of rated power output $(m_{\mathrm{WM}} = -0,75)$ for rotor circuit voltage value k_{ur}=0,23 and maximum rotational frequency of generator's rotor ω_r=1,22 (above the synchronous one by $\Delta\omega$=0,22). The second column of the table reflects the parameters values for minimum generator's rotor rotational frequency ω_r=0,78 ($\Delta\omega$=–0,22) with k_{ur}=0,23. The first two lines define the values of voltage components of infinite power buses in d_0,q_0 axes; for all this q_0 axis is aligned with an axis of real numbers, and d_0 axis – with an axis of imaginary numbers.

The generator's currents i_{gq_0} and i_{gd_0} ("minus" sign corresponds to the current output to the external network, "plus" sign – to the consumption from the network) for ω_r=1,22 change as follows: when voltage increases in the generator's rotor circuit, k_{ur} – real component of the generator's current i_{gq_0} reduces only slightly, and the imaginary component increases significantly with changing its sign from "plus" to "minus", which corresponds to transition from a consumption mode to mode of reactive power output to the external network.

The components of load currents i_{nq_0} and i_{nd_0}, which are determined not only by the set values of constant conductance shunts, but also by the voltage module value at the attachment point of load, vary insignificantly, this change is determined by the voltage module in the node – $U_{nod.0}$. Since the currents in L2 line are determined by the algebraic sum of the currents of generator and load, the negative current sign i_{Lq_0}shows, which component and how much of it is transported to the infinite power buses of power system, and which part is consumed. Consumption of reactive power from a system to generator and load is determined by the current component i_{Ld_0}, which for given parameters of the generator and external network is always positive, i.e. this current flows from the system to load.

Further, in the following table the values of voltage components are shown in a node $U_{nod.q_0}$ and $U_{nod.d_0}$ and on generator terminals (DFIG) U_{gq_0} and U_{gd_0}. As it was indicated, mode options, listed in the second column, correspond to operating mode of WPP with DFIG for ω_r=0,78 and corresponding to it value of the moment $m_{\mathrm{WM}} = -0,35$. In this mode, the generator supplies an active power to network, but consumes reactive one, that the parameters values of the regime reflect.

The fluktogramms, showing the dynamics of the process, are presented in fig. 3 for $m_{\mathrm{WM}} = -0,75$ and $\omega_{r.st}$=1,22 for k_{ur}=0,25, k_{fr}=s=0,22 (algorithm and software of solution are presented in Appendix (case 2)). The fluktogramm of electromagnetic torque change of the generator m_{EM} is presented in curve 3, for all this the connection of generator to infinite power buses is carried out by circuit in fig. 1. For visualization a rare variant of connection is presented, when in a moment of connection the wind speed is equal to the calculated one, and therefore the developed by wind motor torque is $m_{\mathrm{WM}} = -0,75$ (minus sign indicates, that the torque acts pursuant to the electromagnetic torque of generator, i.e. increases the acceleration). Thus, up to 50 radian DFIG running in traction mode, then under the action of the torque m_{WM} goes into the generator one, and from 50 rad. to 500 rad. DFIG operates in generator mode with short–circuited rotor winding (rotor speed ω_r=1,01), and at 500 radian a voltage with amplitude k_{ur}=0,25 and frequency k_{fr}=s=0,22 is applied to the rotor winding, after transient the rotational frequency of rotor is set at the value ω_r=1,22 (fig. 3*b*). Accordingly, the fluctuations of voltage components U_{gd_0} and U_{gq_0} are presented in fig. 3 (*c*, *d*), and currents changes i_{gd_0} and i_{gq_0} are presented in fig.3 (*e* and *f*).

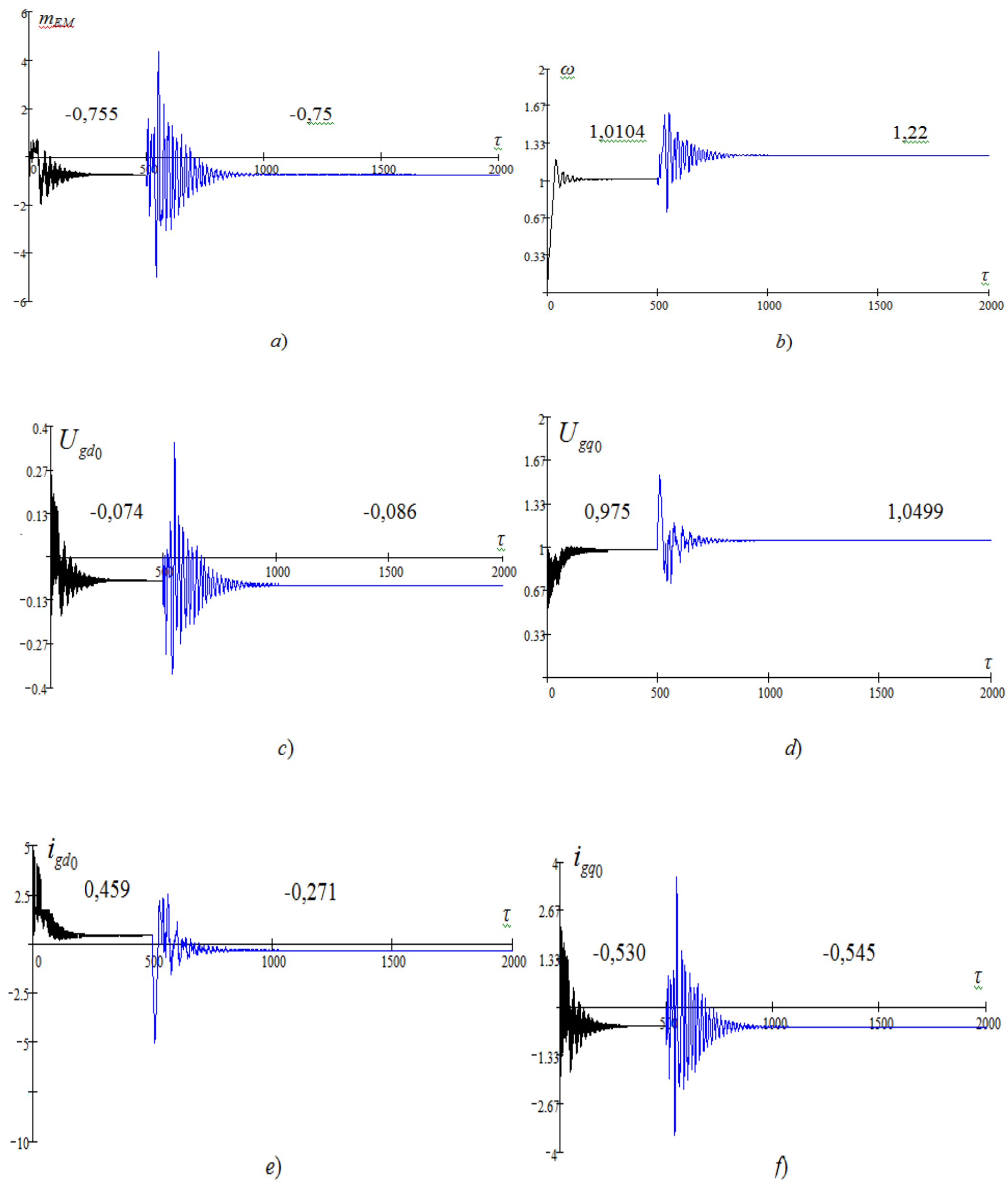


Figure 3. The fluktogramms showing the dynamics of the algorithm and software of solution are presented in Appendix (case 2)).

It can be stated by currents fluktogramms, that up to 500th rad. DFIG is operating in generator mode with delivering the active power to the network (the current sign i_{gq_0} is negative), but with the consumption of reactive power from the network (the current sign i_{gd_0} to $\tau = 500$ rad. is positive). After input of voltage with equal to slip a frequency to rotor winding, current i_{gd_0} changes sign from positive to negative, and the sign of current i_{gq_0} remains unchanged, which indicates, that WPP's generator gives both active and reactive power to the external network. The steady-state values of all parameters for this mode are presented in the table.

3. Conclusion

1. The modeling technique of power system (its part), containing generator of wind power farm carried out on the basis of DFIG, is offered. The developed technique allows to keep the

simplicity and clarity of the modeling of DFIG itself control parameters simultaneously with taking into account the changes of external network parameters.

2. This technique is general one, and can be extended to any kind of power plants, based on the double fed induction generator, used as generators (for example, small hydraulic units).

4. Appendix

Case 1. Parameters of external network: (they are reduced to generator voltage and reference generator resistance) $r_{L"1} = 0,0056$ (parameters reflect the actual project of WPF connection to Republican Power System on Absheron).

Calculated values of factors:

$$\begin{array}{ll} \mathrm{k}_{\mathrm{u}q} = 1,031 & k_{dq} = 1,0006 \\ \mathrm{k}_{\mathrm{u}d} = 0,0247 & k_1 = 1,03 \\ \mathrm{k}_{\mathrm{i}q} = 0,013 & k_2 = 0,0255 \\ \mathrm{k}_{\mathrm{i}d} = 0,1037 & k_3 = 0,015 \end{array} \quad k_4 = 0,1033$$

The equations of generator voltage components U_g with $U_{sd_0} = 0$, $U_{sq_0} = 1$:

$$\left.\begin{array}{l} \mathrm{U}_{gq} = 1,03 \cdot cos\theta - 0,0255 \cdot sin\theta + 0,015 \cdot \mathrm{i}_{gq} - 0,1033 \cdot \mathrm{i}_{gd} \\ \mathrm{U}_{gd} = -1,03 \cdot sin\theta - 0,0255 \cdot sin\theta + 0,1033 \cdot \mathrm{i}_{gq} + 0,015 \cdot \mathrm{i}_{gd} \end{array}\right\}$$

Initial voltages of the infinite capacity buses in synchronously rotating axes d_0, q_0, U_{sd_0} and U_{sq0} have been determined by voltage conversion in axes d, q $\mathrm{U}_d = -1 \cdot sin\theta$ and $\mathrm{U}_q = 1 \cdot cos\theta$ by well-known equations:

$$\begin{array}{l} \mathrm{U}_{sd_0} = \mathrm{U}_q \cdot sin\theta + \mathrm{U}_d \cdot cos\theta \\ \mathrm{U}_{sq_0} = -\mathrm{U}_d \cdot sin\theta + \mathrm{U}_q \cdot cos\theta \end{array}$$

out of condition, that the generator (DFIG) is fed directly from the infinite capacity buses of power system, so naturally:

$$\begin{array}{l} \mathrm{U}_{sd_0} = 1 \cdot cos\theta \cdot sin\theta - 1 \cdot sin\theta \cdot cos\theta = 0 \\ \mathrm{U}_{sq_0} = 1 \cdot sin^2\theta + 1 \cdot cos^2\theta = 1 \end{array}$$

Case 2. Algorithm of "aligning" of DFIG equations with the parameters of external network of power system and software of solution are presented below:

$$D(\tau, Y) = \begin{bmatrix} U_{\mathrm{gd}} + Y_2 - Y_5 \cdot Y_2 - 0,0115 \cdot (4,73 \cdot Y_1 - 4,56 \cdot Y_3) \\ U_{\mathrm{gq}} - Y_1 - Y_5 \cdot Y_1 - 0,0115 \cdot (4,73 \cdot Y_2 - 4,56 \cdot Y_4) \\ -U_s \cdot k_{ur} \cdot \sin(k_{fr} \cdot \tau) - 0,0122 \cdot (4,72 \cdot Y_3 - 4,56 \cdot Y_1) \\ \pm U_s \cdot k_{ur} \cdot \cos(k_{fr} \cdot \tau) \cdot (4,72 \cdot Y_4 - 4,56 \cdot Y_2) \\ 0,03 \cdot (-0,75) - 0,03 \cdot [Y_1 \cdot (4,73 \cdot Y_2 - 4,56 \cdot Y_4) - Y_2 \cdot (4,73 \cdot Y_1 - 4,56 \cdot Y_3)] \\ Y_5 \end{bmatrix}$$

$$Y_0 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}$$

where $Y_1 = \psi_{ds}$, $Y_2 = \psi_{qs}$, $Y_3 = \psi_{dr}$, $Y_4 = \psi_{qr}$, $Y_5 = \omega$, $Y_6 = \theta$, $\mathrm{x}_1 = \mathrm{i}_{ds}$, $\mathrm{x}_2 = \mathrm{i}_{qs}$, $\mathrm{x}_3 = \mathrm{i}_{dr}$, $\mathrm{x}_4 = \mathrm{i}_{\mathrm{qr}}$

$$U_{gd} = -1,03 \cdot sin\theta - 0,0255 \cdot cos\theta + 0,1033 \cdot [4,73 \cdot Y_2 - 4,56 \cdot Y_4 + k_{ur} \cdot (4,72 \cdot Y_2 - 4,56 \cdot Y_4)] + \\ +0,015 \cdot [4,73 \cdot Y_1 - 4,56 \cdot Y_3 + k_{ur} \cdot (4,72 \cdot Y_3 - 4,56 \cdot Y_1)]$$

$$U_{gq} = 1,03 \cdot cos\theta - 0,0255 \cdot \sin\theta + 0,015 \cdot [4,73 \cdot Y_2 - 4,56 \cdot Y_4 + \mathrm{k}_{\mathrm{ur}} \cdot (4,72 \cdot Y_2 - 4,56 \cdot Y_4)] - \\ -0,1033 \cdot [4,73 \cdot Y_1 - 4,56 \cdot Y_3 + \mathrm{k}_{\mathrm{ur}} \cdot (4,72 \cdot Y_3 - 4,56 \cdot Y_1)]$$

$$x_1 = 4,73 \cdot Y_1 - 4,56 \cdot Y_3$$
$$x_2 = 4,73 \cdot Y_2 - 4,56 \cdot Y_4$$
$$x_3 = 4,72 \cdot Y_3 - 4,56 \cdot Y_1$$
$$x_4 = 4,72 \cdot Y_4 - 4,56 \cdot Y_2$$

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SMART GRID IN FUTURE-TECHNOLOGIES & SOLUTIONS

SAEID SHOARI NEJAD [1], JUVARLINSKAYA E.R. [2]

Abstract. Smart grid's definitions and concerns might be different, but EPRI (Electrical Power Research Institute) definition almost covers major concepts and goals of Smart Grid: a power system that serves millions of customers and has an intelligent communications infrastructure enabling the timely, secure and adaptable information flow needed to provide power to the evolving digital economy. In other words, a Smart Grid is comprised of various solutions focused on the integration of two infrastructures: electrical system + information system. The paper will try to cover the available technologies and solutions for smart grid and approach to the subject as business case. The paper, also, will try to cover key Smart Grid applications and some samples.

Keywords: Smart Grid, Electrical System, Information System.

1. Major characteristics

An electric power system is called "smart grid" when it has following characteristics:
1. Self-healing to correct problems early
2. Interactive with consumers and markets
3. Optimized to make best use of resources
4. Secure from threats and hazards
5. Predictive to prevent emergencies
6. Distributed assets and information
7. Integrated to transform data into Information

2. Values of the Smart Grid

Smart grid values are different in various countries and utilities; however, common values for all countries are:

1. Increase energy productivity: Both the utility and consumer could become more efficient, thus saving up to 10% in electric usage while conserving finite natural resources.

2. Increase power reliability and quality: Reduce power disturbances by more than 75% by 2020, thus saving customers in excess of $50 billion through a reduction in outages.

3. Reduce CO2 emissions: Reduce U.S. total carbon emissions up to 25 percent. This would equate to the same CO2 benefits as planting up to 167 million acres of forest (which is equal to the size of Texas) and the NO x benefits of taking up to 130 million cars off the road. This figure changes area by area and over time.

4. Increase safety & security: Reduce potential hazards associated within the grid, by increasing public and worker safety, and ensuring the availability of critical and emergency equipment.

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3. Road Map for a Smart Grid

Road map for a smart grid, regardless of the location, needs to cover following goals:

1. Demand Optimization: This includes "managing peak via controlling power consumptions". It is essential to defer upgrades, optimize generations and renewable. Its values for utilities in the USA are:

a. 15M$/year saving, b. 58K Ton CO_2 reduction c. residential consumer savings up to 10%

The elements of "demand optimization and its various capabilities" are:

1.1-Customer Choice & Control

- Critical Peak Pricing
- Time of Use Rate
- Prepaid Metering
- Demand Response Programs
  - Voluntary or Automatic Control
- Home Energy Management Integrated Net Metering -KWH, KVH, Voltage
- PQ
- Green Power Choices
- CO2 Management Choices
- Usage Management –by Appliance
- Multiple Rate Choices
- Green Energy Supply

1.2-ChoicesDistributed Generation

- PV
- Wind
- Bio-Mass
- Geothermal

1.3-Distributed Storage

- Li-Ion Battery
- Fuel Cells

1.4-Enabling New Programs

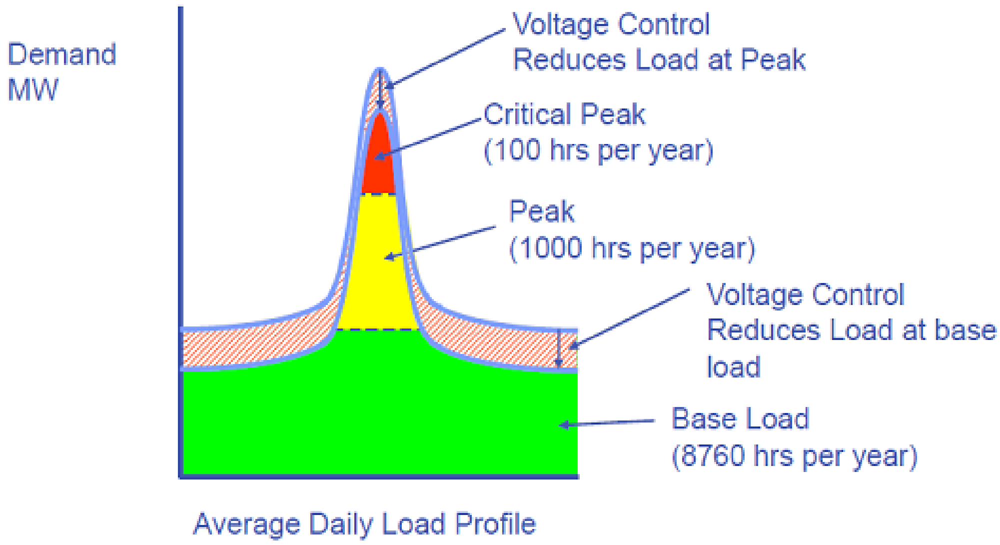
- Load Management Programs
- Distributed Generation
- Storage Management
- Automatic Meter Reading
- New Communications with Customer
- Power Quality Management
- Remote Service Switch
- Cold Load Pickup
- System Cyber Security
- System Management
- Theft Detection

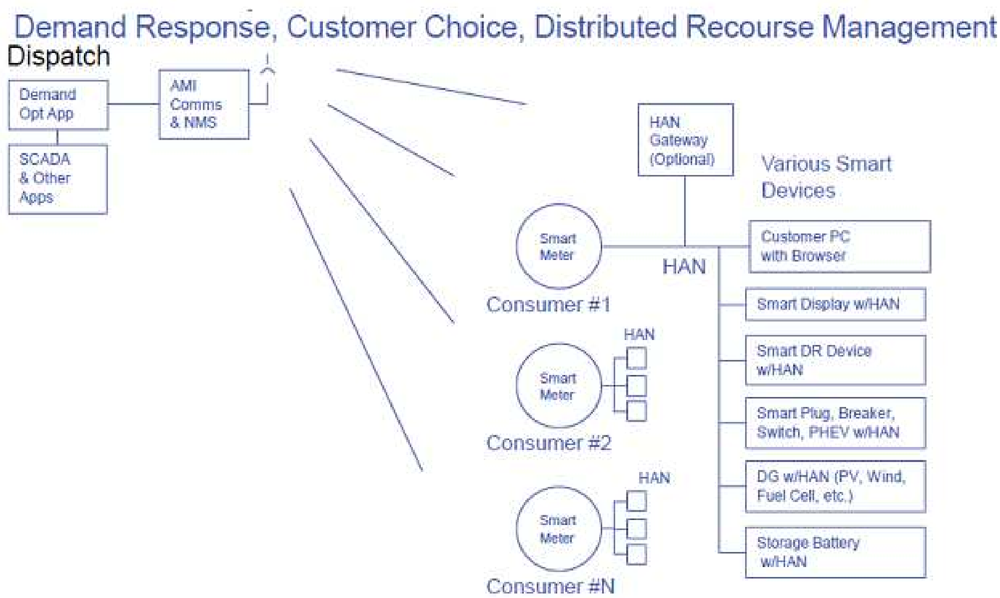
2. Delivery Optimization: This includes "reducing delivery losses in distribution". It is essential to decrease energy wasting and increase profit margins. Its values for utilities in the USA are:

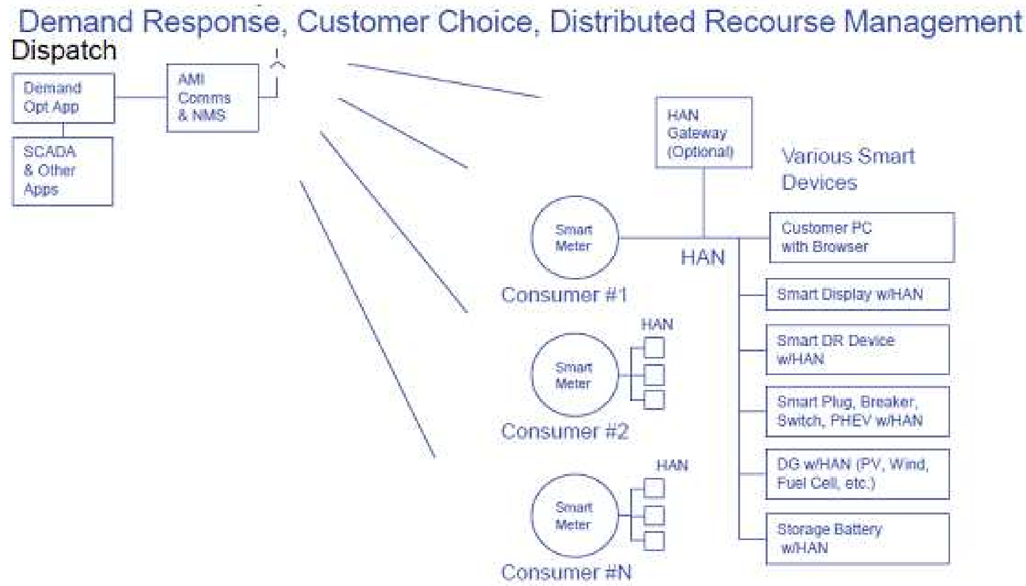
a. 27M$/year saving

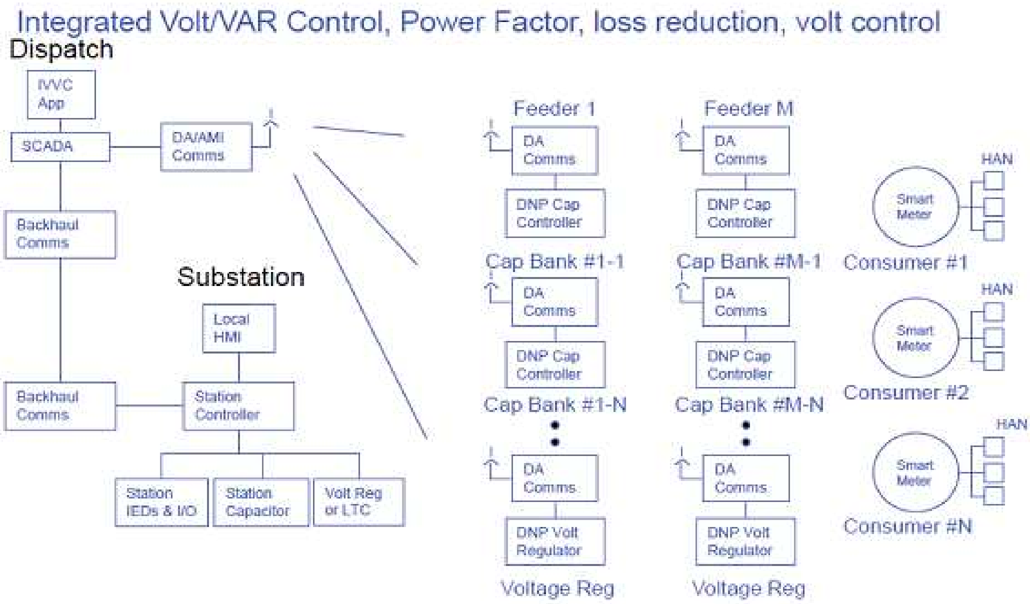
b. 29K Ton CO2 reduction

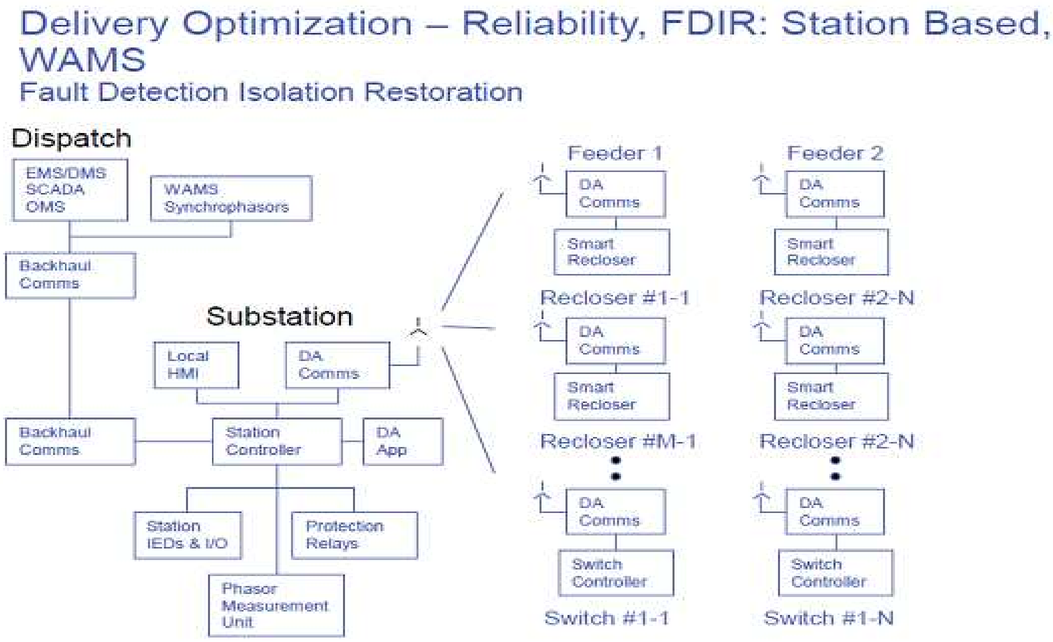
Following flow charts shows the inter-relation of the elements of "Demand Optimization":


Demand
MW
Voltage Control
Reduces Load at Peak
Critical Peak
(100 hrs per year)
Peak
(1000 hrs per year)
Voltage Control
Reduces Load at base
load
Base Load
(8760 hrs per year)
Average Daily Load Profile


Demand Response, Customer Choice, Distributed Recourse Management
Dispatch
Demand
Opt App
SCADA
& Other
Apps
AMI
Comms
& NMS
HAN
Gateway
(Optional)
Various Smart
Devices
Smart
Meter
Consumer #1
HAN
Customer PC
with Browser
Smart Display w/HAN
Smart DR Device
w/HAN
Smart Plug, Breaker,
Switch, PHEV w/HAN
DG w/HAN (PV, Wind,
Fuel Cell, etc.)
Storage Battery
w/HAN
Consumer #2
Consumer #N


Demand Response, Customer Choice, Distributed Recourse Management
Dispatch
Demand Opt App
SCADA & Other Apps
AMI Comms & NMS
HAN Gateway (Optional)
Various Smart Devices
Smart Meter
HAN
Consumer #1
Customer PC with Browser
Smart Display w/HAN
Smart DR Device w/HAN
Smart Plug, Breaker, Switch, PHEV w/HAN
DG w/HAN (PV, Wind, Fuel Cell, etc.)
Storage Battery w/HAN
Consumer #2
Consumer #N


Integrated Volt/VAR Control, Power Factor, loss reduction, volt control
Dispatch
IVVC App
SCADA
DA/AMI Comms
Backhaul Comms
Substation
Local HMI
Station Controller
Station IEDs & I/O
Station Capacitor
Volt Reg or LTC
Feeder 1
Feeder M
DA Comms
DNP Cap Controller
Cap Bank #1-1
Cap Bank #M-1
Cap Bank #1-N
Cap Bank #M-N
DNP Volt Regulator
Voltage Reg
HAN
Smart Meter
Consumer #1
Consumer #2
Consumer #N



The elements of "delivery optimization" and its various capabilities" are:

- **VAR Optimization - Power Factor Correction**

Distribution feeder capacitor bank control is to provide the benefit of energy loss reduction by coordinating capacitor banks control.

- **Conservation Voltage Reduction (CVR)**

Coordinating regulator and LTC control is to reduce feeder voltage levels to provide the benefit of load reduction on the feeders and substation.

- **Integrated Volt/VAR Control (IVVC)**

Coordinated Control of substation transformer tap changers, feeder voltage regulators and capacitor banks are to ensure a VAR and voltage profile to optimize these benefits.

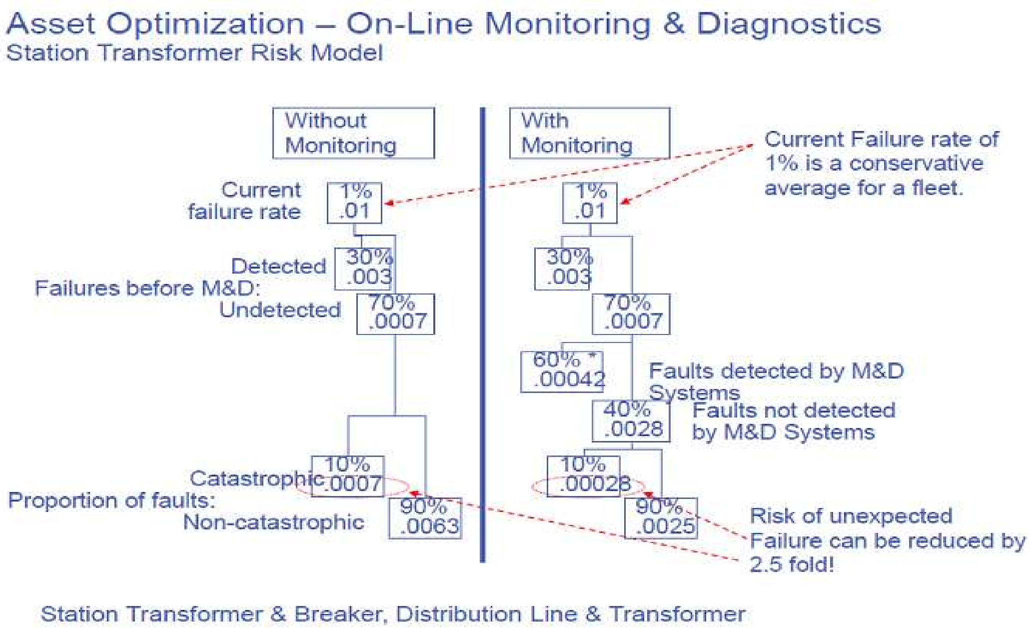
- Typical Benefits - conservation Voltage Reduction
- **Reduce voltage at peak for economics**
- **Reduce voltage across base to reduce demand**
- **Monitoring improves visibility of voltage along circuit**
- **Significant positive PV calculated for Utility and Consumer**
- **Reduced CO_2 emissions**

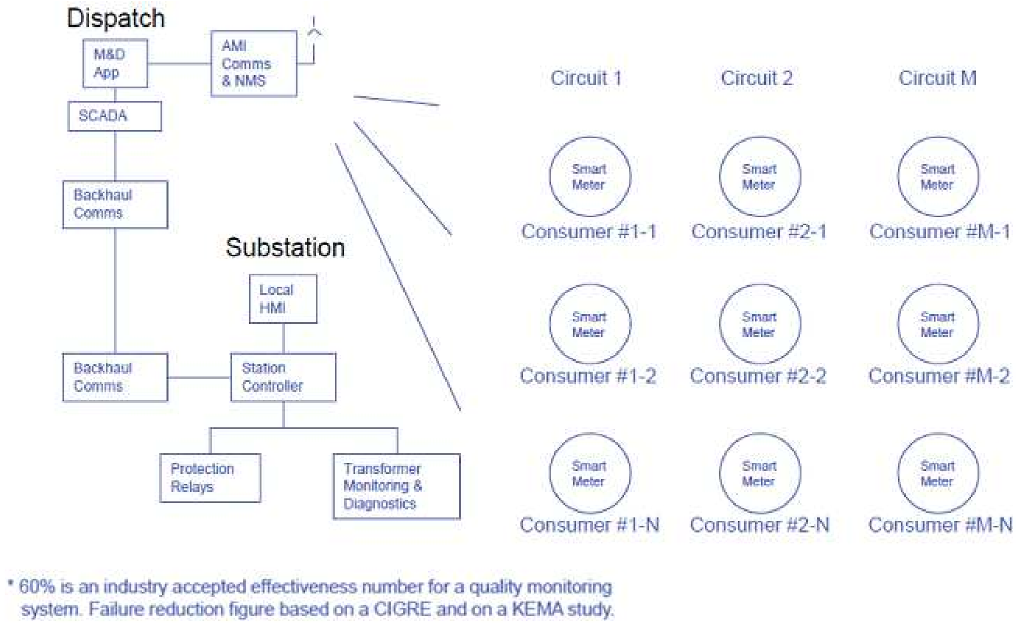
Its benefits include:

- **Improves distribution system efficiency**
- **Reduces distribution line losses**
- **Improves voltage profile**
- **Improves system stability and capacity**
- **Defers capital upgrades**
- **Reduces energy demand**

1. Asset Management: This includes "prognostics for proactive equipment maintenance". It is essential to reduce outages and focusing on maintenance responsible bodies. Its value for utilities in the USA is 12M$/year.

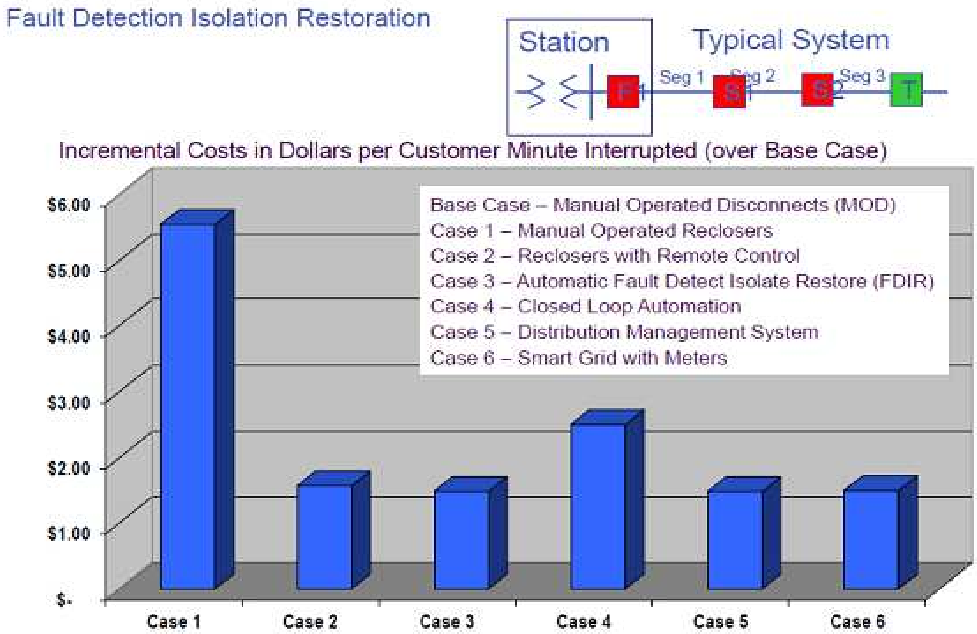
The following flow chart shows inter-relations of "Asset management" elements:





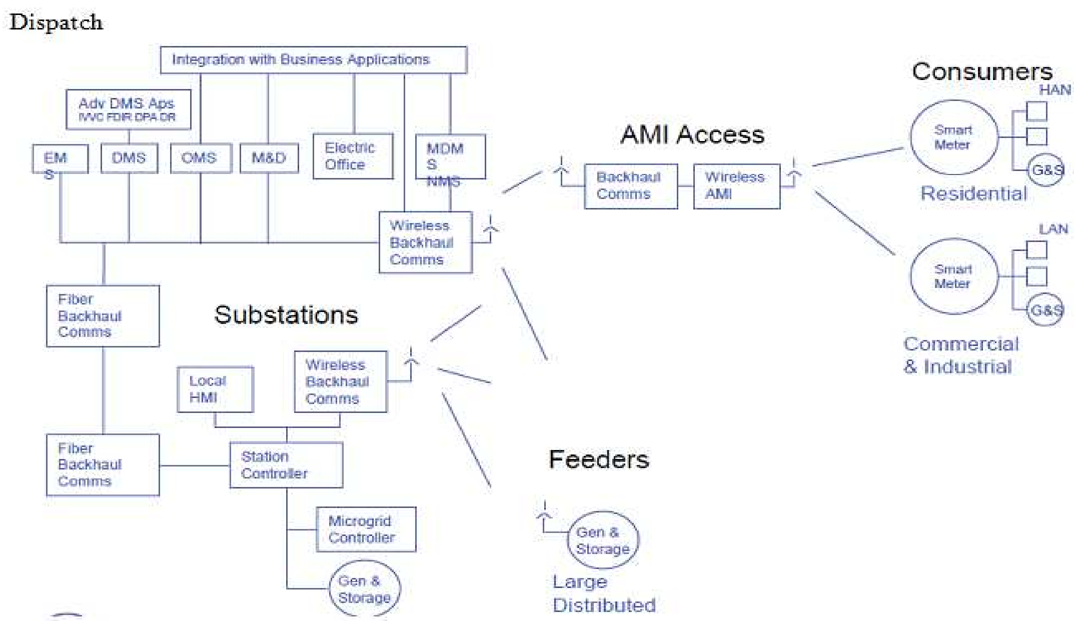
2. Reliability Optimization: This includes "wide area protection and control". It is essential to increase network performance and reliability. Its value for the utilities in the USA is 21M$/year, if a "four hour blackout/year" happens in a transmission utility.

Reliability, FDIR (station based) example is as follows:



3. Renewable Optimization: This includes "using forecasting & smoothing". It is essential for compensating production variability especially in areas with weak grids.

Integration of generation and storage example is as follows:



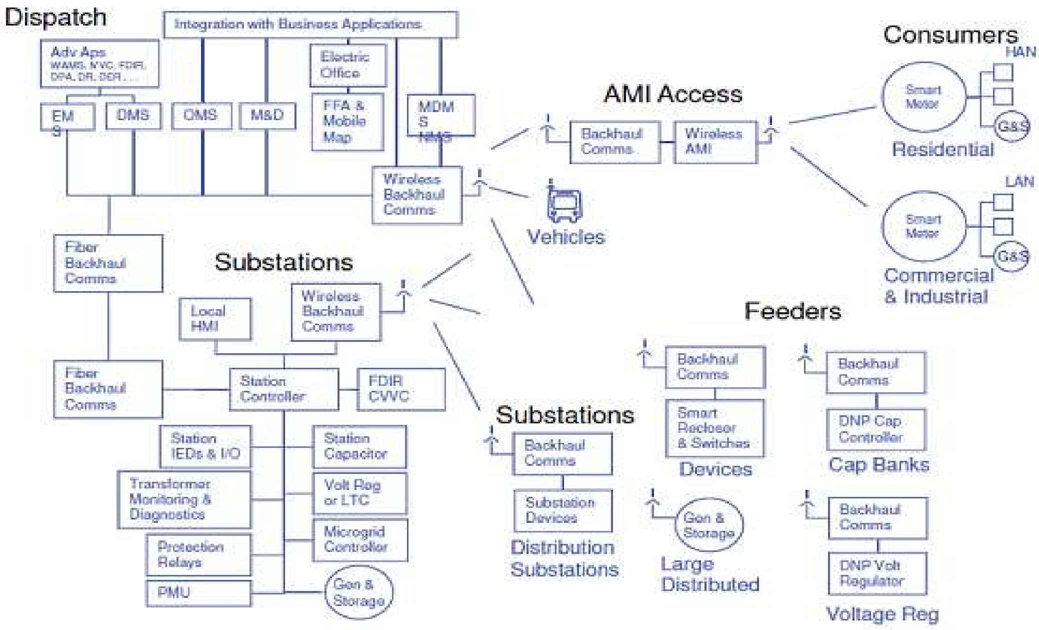
Renewable optimization future benefits are:

1. Improves the market and value proposition for renewable and storage by adding energy management and demand response technologies
2. Includes load shedding functions in response to demand response prompts, as well as to establish a dynamically reconfigurable critical bus for backup operation
3. Reactive power functions, including voltage regulation and VAR support
4. Micro-grid and Islanding support
5. Grid support including frequency droop, reserve and curtailment

6. Advanced communications interface between utility operators and commercial/utility systems

4. Summary

The following flow diagram shows an open and integrated smart grid view:



5. Conclusion

The smart grid provides incremental improvements to each function *"Demand Optimization + Delivery Optimization + Asset Optimization + Reliability Optimization + Renewable Optimization"*

Developing grid communications, generation, transmission, distribution and consumer products that tie into today's smart grid investments.

Smart grid challenges are going to provide the following benefits from both utilities and consumers' perspectives:

Benefits & Costs – Proving the business benefits of the SG system that achieve the business & technical objectives to drive Stimulus Applications

Smart Grid Road Map – Separating the hype from the available and prioritizing resources

Data – Provide & maintain accurate & secure network model that is synchronized with asset data & work management processes, shared across operating departments.

Analytics - Provide analytics to turn raw data into actionable information to support real time decision support

Visualization - Provide state of the art visualization tools that provides understandable & actionable information

Technology Migration - Provide a systems design that utilize legacy tools yet facilitates migration to next generation technology.

Users – Dramatic change management required. Evolution, not revolution

Safety – Ensure that systems are designed and personnel are trained on new operating practices to maintain a high level of

Security – Ensure that systems meet the utility and regulator's security requirements

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FUZZY RELIABILITY ANALYSIS OF A GAS POWER PLANT USING T_ω -BASED ARITHMETIC OPERATIONS ON L - R TYPE FLAT VAGUE SET

MANJIT VERMA[1], AMIT KUMAR[1]

Abstract. In this paper, definitions of the L - R type flat vague set and arithmetic operations between L - R type flat vague set are introduced. For preserving the shape of the L - R type flat vague sets T_w -based arithmetic operations are used, also it simplify vague set arithmetic operations and even get the exact solutions for system reliability. Furthermore, with the help of the failure modes for the different components of a gas power plant, a fault tree is constructed. An expression is obtained for evaluating the probability of failure of a gas power plant using minimal cut set approach. Using the proposed approach and minimal cut set of the constructed fault tree, the fuzzy reliability of a gas power plant is evaluated. By using this approach, fuzzy system reliability can be analyzed in a more flexible and more intelligent manner.

Keywords: Fuzzy Reliability, Vague Set, L - R type flat vague set, Fault Tree, Gas Power Plant.

1. Introduction

Traditionally, the reliability of a system behavior is fully characterized in the context of probability measures. The outcome probability of the top event is certain and precise as long as the assignment of the basic events are descent from reliable information. However, in real system, the information is inaccurate and supposed to have linguistic representation. The estimation of precise values of the probabilities becomes very difficult in many applications. Therefore, in order to handle the insufficient information; the fuzzy approach [1] is used to evaluate the system reliability.

Singer [2] presented a fuzzy set approach for fault tree and the reliability analysis in which the relative frequencies of the basic events are considered as fuzzy numbers. Cai et al.[3,4] proposed a different insight by introducing the possibility assumption and fuzzy state assumption to replace the probability and binary state assumptions. Cheng and Mon [5] presented a method for fuzzy system reliability analysis using interval arithmetic operations of fuzzy numbers. The methods presented in [2,5] require a large amount of computational time because of their complex arithmetic operations. Therefore, Chen [6] proposed simplified fuzzy arithmetic operations for analyzing the fuzzy system reliability.

Hong and Do [7] analysed fuzzy system reliability by the use of sup- T_ω convolution on fuzzy arithmetic operations and they have shown that their approach can simplify fuzzy arithmetic operations and even got the exact solutions for L - R type fuzzy system reliability, while others [2,5,6] have got the approximate solutions.

Pan and Yun [8] used the fuzzy set theory for modeling the fuzzy system structure and proposed the new procedure to calculate the system reliability. Chanda and Bhattacharjee [9] presented a fuzzy fault tree based reliability analysis of an optimally planned transmission system. Verma et al. [10] optimized the reactive power control variables by using fuzzy linear programming and by considering the voltage collapse phenomena in the existing framework of Bulk Power System Reliability Evaluation (BPSRE).

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Fuzzy set theory has been shown to be useful tool to handle the situations, in which the data is imprecise, by attributing a degree to which a certain object belongs to a set. In real life, a person may assume that an object belongs to a set, but it is possible that he is not sure about it. In other words, there may be hesitation or uncertainty that whether an object belongs to a set or not. In fuzzy set theory, there is no means to incorporate such type of hesitation or uncertainty. A possible solution is to use vague set [11].

Chen [12] presented the arithmetic operations between vague sets and a new method for analyzing the fuzzy system reliability based on vague sets. Kumar et al. [13] presented fuzzy reliability analysis of marine power plant using vague set theory, where the reliability of components of the system is represented by trapezoidal vague sets defined on the universe of discourse [0,1]. Shu et al. [14] proposed an algorithm to calculate the fault interval of system components in terms of providing the possibilities of failure of bottom events using intuitionistic fuzzy fault tree analysis and applied their method to the failure analysis problem of Printed Circuit Board Assembly (PCBA).

Kumar et al. [15] developed a method for analyzing system reliability by using interval valued vague sets, and applied it for the reliability analysis of a marine power plant. Kumar et al. [16] introduced definition of L - R type triangular vague set, T_ω -based arithmetic operations between two L - R type triangular vague sets and vague success tree for fuzzy reliability analysis. Chang and Cheng [17] obtained fault interval and reliability interval of the PCBA with different membership function using fault-tree analysis. Taheri and Zarei [18] investigated bayesian system reliability assessment in vague environment.

The rest of this paper is organized as follow: In Section 2, basic definitions of L - R type flat vague set and T_ω -based arithmetic operations between L - R type flat vague set are introduced. In Section 3, gas power plant is used to illustrate the proposed method. Experimental results of proposed approach and other approaches are discussed. The comparisons of proposed approach with other approaches are discussed in Section 4 and the final section make conclusions.

2. Preliminaries

This section gives the brief overview of some basic definitions of vague set theory and T_ω-based arithmetic operations between L - R type flat vague set which are of useful in our further consideration.

2.1. **Basic definitions. Definition 2.1 [11]** A vague set $\tilde{V}$ in a basic set X is characterized by a truth membership function $t_{\tilde{V}}, t_{\tilde{V}} : X \to [0,1]$ and a false membership function $f_{\tilde{V}}, f_{\tilde{V}} : X \to [0,1]$. If generic element of X is denoted by 'x_i', then the lower bound on the membership grade of x_i derived from evidence for x_i is denoted by $t_{\tilde{V}}(x_i)$ and the lower bound on the negation of x_i is denoted by $f_{\tilde{V}}(x_i)$; $t_{\tilde{V}}(x_i)$and $f_{\tilde{V}}(x_i)$ both associate a real number in the interval [0,1] with each point in x_i where, $t_{\tilde{V}}(x_i) + f_{\tilde{V}}(x_i) \leq 1$. A vague set $\tilde{V}$ in the universe of discourse X is shown in Figure 1.

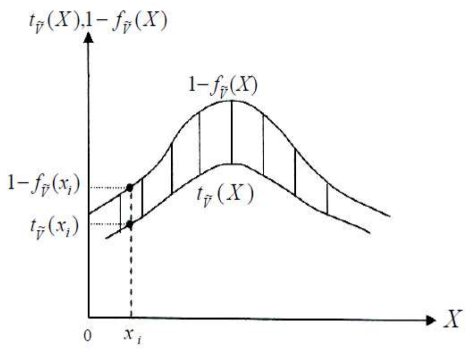

Figure 1. Vague set representation.

when X is continuous, a vague set $\tilde{V}$ can be written as:

$$\tilde{\mathrm{V}} = \int_x \left[t_{\tilde{V}}(x_i), 1 - f_{\tilde{V}}(x_i)\right] \Big/ x_i; x_i \in X$$

when X is discrete, a vague set $\tilde{V}$ can be written as:

$$\tilde{V} = \sum_{i=1}^{n} \left[t_{\tilde{V}}(x_i), 1 - f_{\tilde{V}}(x_i)\right] / x_i; x_i \in X$$

Definition 2.2 [16] A *L-R* type vague set $\tilde{V} =< [(m,\alpha,\beta)_{LR};\mu;\nu] >$is said to be a *L-R* type triangular vague set $\tilde{V}$ if its membership function is given by:

$$t_{\tilde{V}}(x) = \begin{cases} \mu L\left(\frac{m-x}{\alpha}\right), x \le m, \alpha > 0 \\ \mu \qquad\qquad , \mathrm{x = m} \\ \mu \mathrm{R}\left(\frac{\mathrm{x-m}}{\beta}\right), x \ge m, \beta > 0 \end{cases} \qquad 1 - f_{\tilde{V}}(x) = \begin{cases} \nu L\left(\frac{m-x}{\alpha}\right), \ \mathrm{x \le m}, \alpha > 0 \\ \nu \qquad\qquad , \mathrm{x = m} \\ \nu \mathrm{R}\left(\frac{\mathrm{x-m}}{\beta}\right), x \ge m, \beta > 0 \end{cases}$$

where, $t_{\tilde{V}}(x)$ and $1 - f_{\tilde{V}}(x)$are membership value and complement of non-membership value respectively, $m \in R$ is the center, $\alpha > 0$ is the left spread, $\beta > 0$ is the right spread of $\tilde{V}$;μ and ν; m and v are real numbers such that $0 \le \mu \le \nu \le 1$; L and R are non-increasing and continuous functions from [0,1] to [0,1].

Definition 2.3 A *L-R* type vague set $\tilde{V} =< [(m,n,\alpha,\beta)_{LR};\mu;\nu] >$ is said to be a *L-R* type flat vague set $\tilde{V}$ if its membership function is given by:

$$t_{\tilde{V}}(x) = \begin{cases} \mu L\left(\frac{m-x}{\alpha}\right), \ \mathrm{x \le m}, \alpha > 0 \\ \mu \qquad\qquad , \mathrm{m \le x \le n} \\ \mu \mathrm{R}\left(\frac{\mathrm{x-n}}{\beta}\right), x \ge n, \beta > 0 \end{cases} \qquad 1 - f_{\tilde{V}}(x) = \begin{cases} \nu L\left(\frac{m-x}{\alpha}\right), x \le m, \alpha > 0 \\ \nu \qquad\qquad , \mathrm{m \le x \le n} \\ \nu \mathrm{R}\left(\frac{\mathrm{x-n}}{\beta}\right), x \ge n, \beta > 0 \end{cases}$$

where, $m, n \in R$ is the center, $\alpha > 0$ is the left spread, $\beta > 0$ is the right spread of $\tilde{V}$; $\mu$and ν are real numbers such that $0 \le \mu \le \nu \le 1$and L, R are non-increasing and continuous functions from [0,1] to [0,1]. Also, the degree of the indeterminacy membership (hesitation) is given by:

$$\pi_{\tilde{V}}(x) = 1 - t_{\tilde{V}}(x) - f_{\tilde{V}}(x).$$

2.2. T_ω- based arithmetic operations between two *L - R* type flat vague sets

Let $T = T_\omega$ be the weakest t-norm and $\tilde{V}_1 =< [(m_1,n_1,\alpha_1,\beta_1)_{LR};\mu_1;\nu_1] >$,
$\tilde{V}_2 =< [(m_2,n_2,\alpha_2,\beta_2)_{LR};\mu_2;\nu_2] >$ be two *L- R* type flat vague sets. The T_ω-based arithmetic operations between $\tilde{V}_1$ and $\tilde{V}_2$ are defined as follows:

$$(i) \quad \tilde{V}_1 \oplus_T \tilde{V}_2 =< [(m_1 + m_2, \mathrm{n}_1 + n_2, \max(\alpha_1,\alpha_2) \max(\beta_1,\beta_2))_{LR}; \min(\mu_1,\mu_2); \min(\nu_1,\nu_2)] >$$

$$(ii) \quad \tilde{V}_1 \Theta_T \tilde{V}_2 =< [(m_1 - n_2 \ \mathrm{n}_1 - m_2, \max(\alpha_1,\alpha_2), \max(\beta_1,\beta_2))_{LR} \min(\mu_1,\mu_2); \min(\nu_1,\nu_2)] >$$

(iii) $\tilde{V}_1 \otimes_T \tilde{V}_2 \cong< [(m_1 m_2, n_1 n_2, \ \max(\alpha_1 m_2, \alpha_2 m_1), \max(\beta_1 n_2, \beta_2 n_1))_{LR}; \min(\mu_1,\mu_2); \min(\nu_1,\nu_2)] >$

3. Numerical Verification

3.1. Overview

In this section, an illustrative example of a gas power plant is presented in order to demonstrate the procedure that is proposed in this paper. The first step is to construction of the fault tree of a gas power plant that allows the definition of the functional/logical links between the equipment subsystems. Although all gas turbines possess essentially the same subsystems, such as compressor, combustion chamber, alternator (generator) and turbine, still there are differences between the technologies used by the manufacturers; therefore the fault tree must be developed for each specific gas turbine model. The failure events and different components [19, 20, 21] of a gas power plant are represented by different symbols that are shown below in Table 1.

Table 1.Failure events of a gas power plant.

Failure of total system (T)	Failure of cylinder of exhaust system (I_5)	Casing of the casing system damaged (F_5)
Failure of electric generator system (T_1)	Failure of exhaust connection (I_6)	Pad of the casing system got ruptured (F_6)
Failure of starting/governing system (K)	Failure of Turning gear system of the governing system (K_1)	Housing of the trust bearing got broken (F_7)
Failure of air – inlet system (C)	Failure of start – up system of the governing system (K_2)	Shoes of the trust bearing got broken (F_8)
Failure of turbine system (I)	Failure of gearbox system of the governing system (K_3)	Filler ring of the trust bearing got broken (F_9)
Failure of combustion system (G)	Failure of torque converter of the governing system (K_4)	Failure cooling system of the lubrication System (F_{10})
Failure of compressor system (E)	Casing of the generator got damaged (B_1)	Pressure gauge got corrupted (F_{11})
Generator fail to generate output voltage (T_2)	Rotor bowing of the generator (B_2)	Failure of heating system (F_{12})
Failure of excitation system of generator (T_3)	Guide ways of the generator got damaged (B_3)	Failure of temperature sensor (F_{13})
Turbine unable to reach at desired speed (T_4)	Earth fault occur in generator (B_4)	Failure of Flame tube of the shell (H_1)
Improper pressure/velocity of gas supplied to turbine blades (T_5)	Copper dusting occur in the generator (B_5)	Failure of cylinder of the shell (H_2)
Loose coupling of shaft (T_6)	Failure of generator due to reverseVoltage (B_6)	Spring of the igniter system got broken (H_3)
Improper burning of fuel (T_7)	Failure of generator due to inter turn fault (B_7)	Piston of the igniter system got broken (H_4)
Low/high pressure of air inlet coming from compressor (T_8)	Failure of generator due to short circuit fault(B_8)	Failure of igniter of the igniter system (H_5)
Generator got physical damage (A_1)	Too early operation of human operator (B_9)	Vessels of the cooling system blocked (H_6)
Generator got trip due to electric faults (A_2)	Too late operation of human operator (B_{10})	Bypass valve of the cooling system failed to open (H_7)
Electric faults occur in generator (A_3)	Out of sequence operation by human operator (B_{11})	Control system of the cooling system failed (H_8)
Fault occur in generator due to wrong human operations (A_4)	Delay in open the relay contact (B_{12})	Transition piece of the basket got damaged (H_9)
Failure of relay system (A_5)	Relay contacts freeze (B_{13})	Burner of basket got damaged (H_{10})
Faults occur in generator due to wrong operation of fuse (A_6)	Relay contacts bounce (B_{14})	Vanes got damaged (J_1)
Failure of evaporator cooler system (C_1)	Relay coil burn out (B_{15})	Pins of the vane system got broken (J_2)
Failure of water supply system (C_3)	Fuse open on low current (B_{16})	Blade rings of the turbine cylinder system got broken (J_3)

Pipe section of water supply system got rupture (C_4)	Fuse fails to open on high current (B_{17})	Blade rings of the turbine cylinder system got broken(J_4)
Faulty pump system of water supply system (C_5)	Fuse partially opened (B_{18})	Blade of the turbine cylinder system got broken (J_5)
Valves failed to open on demand (C_6)	Humid Badges burst (D_1)	Failure of exhaust collector of the exhaust system (J_6)
Motor in pump system got damaged (C_7)	Pipes of water supply system got broken (D_2)	Failure of pads of the radial bearing (J_7)
Seal house got ruptured (C_8)	Pipes of water supply system got corrosive (D_3)	Failure of thermocouple in the radial bearing system (J_8)
Motor got overheating (C_9)	Mechanical fault occur in valves of the pump (D_4)	Shell of the radial bearing system got damaged (J_9)
Blade system of compressor got corrupted (E_1)	Valves of the pump fails to receives control signal (D_5)	Static seal of the exhaust system got damaged (J_{10})
Failure of journal bearing of compressor (E_2)	Pump motor insulation failure (D_6)	Exhaust pipes of the exhaust system got damaged (J_{11})
Failure of trust bearing of compressor (E_3)	High current flows in motor circuit (D_7)	Casing of the exhaust cylinder got damaged (J_{12})
Failure of casing system in journal bearing (E_4)	No power supply at the motor terminal (D_8)	Ballooning of torque converter (L_1)
Failure of Lubrication system (E_5)	Seal house rupture due to high temperature (D_9)	Clutch of the torque converter got broken (L_2)
Less water supply coming from reservoir (E_6)	Seal house rupture due to dryness (D_{10})	Gearbox bearing got vibration (L_3)
Wear and tear occurs in shell of combustion system (G_1)	Motor overload (D_{11})	Gearbox self shifting clutch got broken (L_4)
Failure of igniter system (G_2)	Motor got overheating due to failure of cooling system (D_{12})	Gearbox suffers from excessive hogging (L_5)
Failure of cooling system of combustion system (G_3)	Failure of motor due to wrong connection (D_{13})	Loss of field to the main exciter (U_1)
Basket of shell got damaged (G_4)	Filter system got clogged (D_{14})	Short circuit fault occur in the field circuit (U_2)
Failure of vane system turbine (I_1)	Rings of the blade system got broken (F_1)	Loss of a, c supply to the excitation (U_3)
Failure of radial bearings of the turbine (I_2)	Inlet guide vane of the blades system got broken (F_2)	Stress on the coupling of shaft (U_4)
Failure of cylinder of the turbine (I_3)	Shaft of the blade system starts vibrate (F_3)	Loose connectivity (U_5)
Failure of exhaust system of the turbine (I_4)	Stationary blades of the casing system got broken (F_4)	-

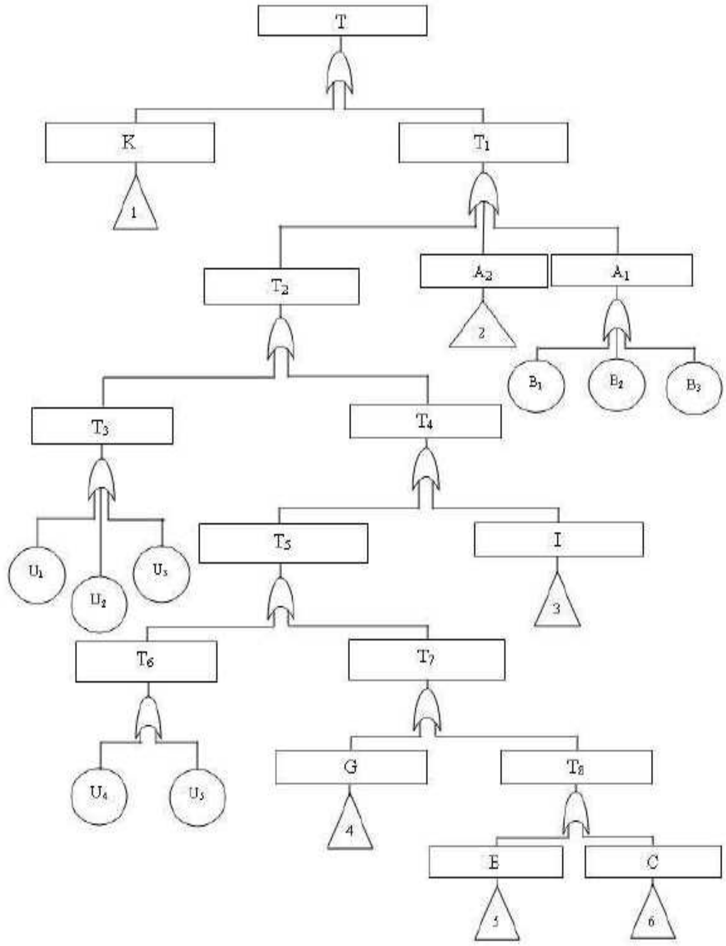

Figure 2. Fault tree of a gas power plant.

The fault tree of a gas power plant is shown in Figure 2, was divided into six main subsystems: air inlet, compressor, combustion, turbine, generator and governing (start/stop subsystem). Those subsystems are further divided into components as shown in Figure 3 to Figure 8, each one performing a specific function in connection with the subsystem main function. A failure in a component at the bottom of the fault tree affects all subsystems above it, causing a possible degradation in the system operation. The fault tree was developed according to the operation manual furnished by the manufacturer.

At last using the minimal cut set approach the reliability of a gas power plant is evaluated in the terms of the bottom events of the constructed fault tree. This research uses logical "AND" and "OR" gate for connecting the fault tree of a gas power plant.

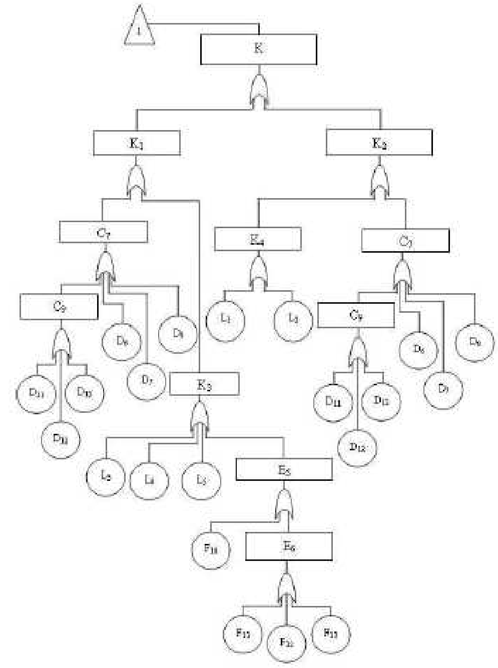

Figure 3.Fault tree of starting/ governing system.

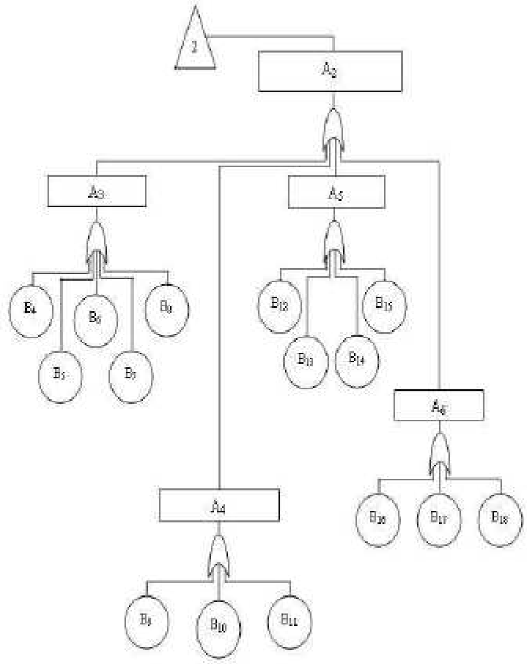

Figure 4. Fault tree of generator system.

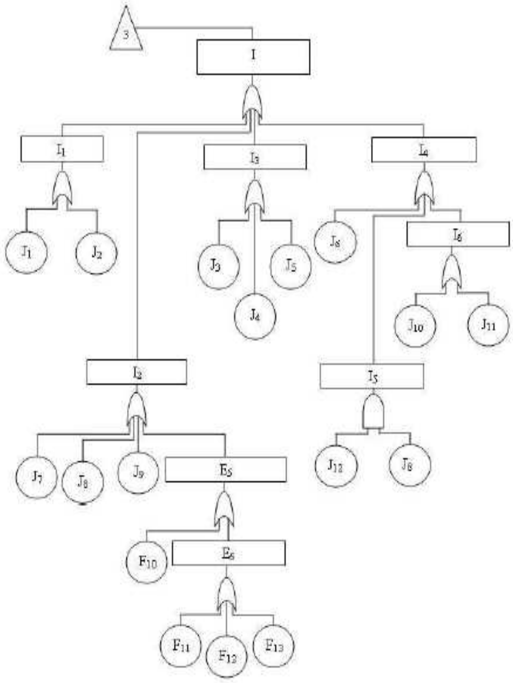

Figure 5.Fault tree of turbine system.

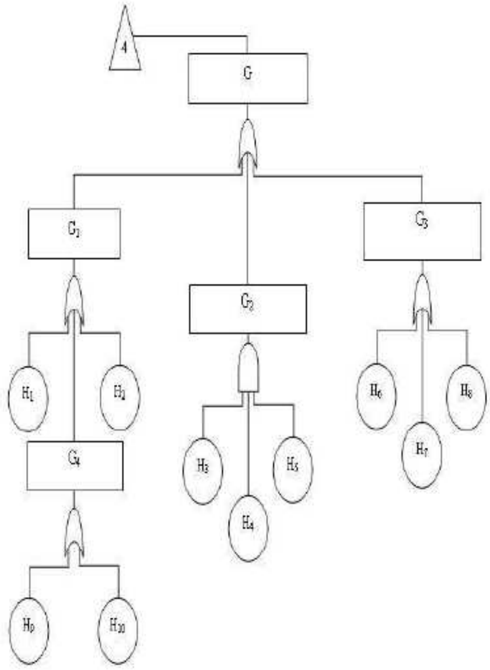

Figure 6. Fault tree of combustion system.

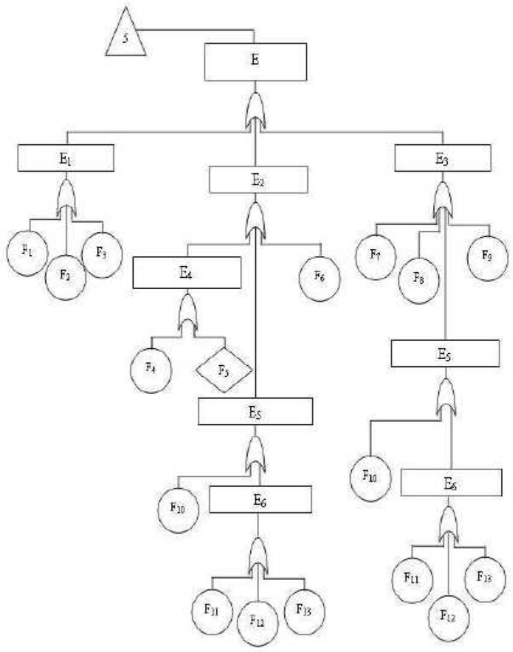

Figure 7.Fault tree of compressor system.

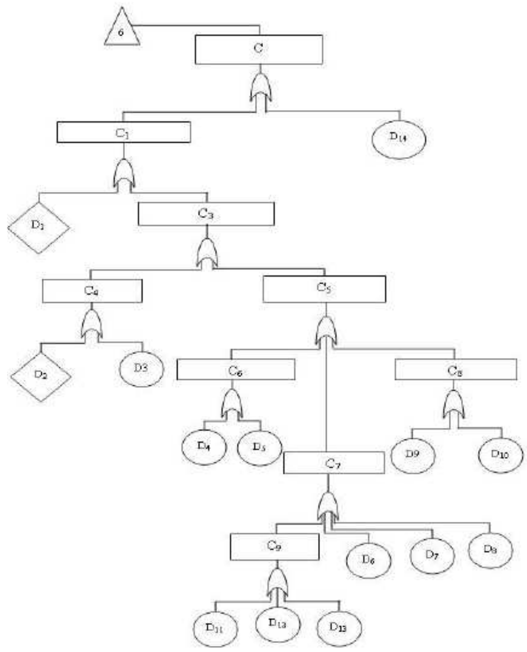

Figure 8. Fault tree of air-inlet system.

The fuzzy Reliability of the TOP event of the system in the term of its bottom event is given below:

$$\tilde{R}_T =$$

$$(1\Theta((1\Theta\tilde{R}_{B_1})\otimes(1\Theta\tilde{R}_{B_2})\otimes(1\Theta\tilde{R}_{B_3})\otimes(1\Theta\tilde{R}_{B_4})\otimes(1\Theta\tilde{R}_{B_5})\otimes(1\Theta\tilde{R}_{B_6})\otimes(1\Theta\tilde{R}_{B_7})\otimes(1\Theta\tilde{R}_{B_8})$$
$$\otimes(1\Theta\tilde{R}_{B_9})\otimes(1\Theta\tilde{R}_{B_{10}})\otimes(1\Theta\tilde{R}_{B_{11}})\otimes(1\Theta\tilde{R}_{B_{12}})\otimes(1\Theta\tilde{R}_{B_{13}})\otimes(1\Theta\tilde{R}_{B_{14}})\otimes(1\Theta\tilde{R}_{B_{15}})\otimes(1\Theta$$
$$\tilde{R}_{B_{16}})\otimes(1\Theta\tilde{R}_{B_{17}})\otimes(1\Theta\tilde{R}_{B_{18}})\otimes(1\Theta\tilde{R}_{D_1})\otimes(1\Theta\tilde{R}_{D_2})\otimes(1\Theta\tilde{R}_{D_3})\otimes(1\Theta\tilde{R}_{D_4})\otimes(1\Theta\tilde{R}_{D_5})\otimes(1$$
$$\Theta\tilde{R}_{D_6})\otimes(1\Theta\tilde{R}_{D_7})\otimes(1\Theta\tilde{R}_{D_8})\otimes(1\Theta\tilde{R}_{D_9})\otimes(1\Theta\tilde{R}_{D_{10}})\otimes(1\Theta\tilde{R}_{D_{11}})\otimes(1\Theta\tilde{R}_{D_{12}})\otimes(1\Theta\tilde{R}_{D_{13}})\otimes($$
$$1\Theta\tilde{R}_{D_{14}})\otimes(1\Theta\tilde{R}_{F_1})\otimes(1\Theta\tilde{R}_{F_2})\otimes(1\Theta\tilde{R}_{F_3})\otimes(1\Theta\tilde{R}_{F_4})\otimes(1\Theta\tilde{R}_{F_5})\otimes(1\Theta\tilde{R}_{F_6})\otimes(1\Theta\tilde{R}_{F_7})\otimes(1$$
$$\Theta\tilde{R}_{F_8})\otimes(1\Theta\tilde{R}_{F_9})\otimes(1\Theta\tilde{R}_{F_{10}})\otimes(1\Theta\tilde{R}_{F_{11}})\otimes(1\Theta\tilde{R}_{F_{12}})\otimes(1\Theta\tilde{R}_{F_{13}})\otimes(1\Theta\tilde{R}_{H_1})\otimes(1\Theta\tilde{R}_{H_2})\otimes(1$$
$$\Theta(\tilde{R}_{H_3}\otimes\tilde{R}_{H_4}\otimes\tilde{R}_{H_5}))\otimes(1\Theta\tilde{R}_{H_6})\otimes(1\Theta\tilde{R}_{H_7})\otimes(1\Theta\tilde{R}_{H_8})\otimes(1\Theta\tilde{R}_{H_9})\otimes(1\Theta\tilde{R}_{H_{10}})\otimes(1\Theta\tilde{R}_{J_1})$$
$$\otimes(1\Theta\tilde{R}_{J_2})\otimes(1\Theta\tilde{R}_{J_3})\otimes(1\Theta\tilde{R}_{J_4})\otimes(1\Theta\tilde{R}_{J_5})\otimes(1\Theta\tilde{R}_{J_6})\otimes(1\Theta\tilde{R}_{J_7})\otimes(1\Theta\tilde{R}_{J_8})\otimes(1\Theta\tilde{R}_{J_9})\otimes$$
$$(1\Theta\tilde{R}_{J_{10}})\otimes(1\Theta\tilde{R}_{J_{11}})\otimes(1\Theta\tilde{R}_{J_{12}})\otimes(1\Theta\tilde{R}_{L_1})\otimes(1\Theta\tilde{R}_{L_2})\otimes(1\Theta\tilde{R}_{L_3})\otimes(1\Theta\tilde{R}_{I_4})\otimes(1\Theta\tilde{R}_{L_8})\otimes(1$$
$$\Theta\tilde{R}_{U_1})\otimes(1\Theta\tilde{R}_{U_2})\otimes(1\Theta\tilde{R}_{U_3})\otimes(1\Theta\tilde{R}_{U_4})\otimes(1\Theta\tilde{R}_{U_5}))) \qquad \text{(i)}$$

Table 2. Basic events failure probability in the from of L – R type flat vague set.

$\tilde{R}_{B_1} =< \left[(0.039,\ 0.040,\ 0.001,\ 0.001)_{LR}; 0.7; 0.8\right] >$	$\tilde{R}_{F_8} =< \left[(0.009,\ 0.010,\ 0.001,\ 0.001)_{LR}; 0.67; 0.91\right] >$
$\tilde{R}_{B_2} =< \left[(0.069,\ 0.070,\ 0.001,\ 0.001)_{LR}; 0.5; 0.8\right] >$	$\tilde{R}_{F_9} =< \left[(0.010,\ 0.011,\ 0.001,\ 0.001)_{LR}; 0.72; 0.88\right] >$
$\tilde{R}_{B_3} =< \left[(0.009,\ 0.010,\ 0.001,\ 0,001)_{LR}; 0.5; 0.7\right] >$	$\tilde{R}_{F_{10}} =< \left[(0.008,\ 0.009,\ 0.001,\ 0.001)_{LR}; 0.65; 0.89\right] >$
$\tilde{R}_{B_4} =< \left[(0.001,\ 0.001,\ 0,0)_{LR}; 0.6; 0.8\right] >$	$\tilde{R}_{F_{11}} =< \left[(0.022,\ 0.023,\ 0.001,\ 0.001)_{LR}; 0.7; 0.8\right] >$
$\tilde{R}_{B_5} =< \left[(0.019,\ 0.020,\ 0.001,\ 0.001)_{LR}; 0.7; 0.8\right] >$	$\tilde{R}_{F_{12}} =< \left[(0.024,\ 0.025,\ 0.001,\ 0.001)_{LR}; 0.7; 0.75\right] >$
$\tilde{R}_{B_6} =< \left[(0.029,\ 0.030,\ 0.001,\ 0.001)_{LR}; 0.65; 0.8\right] >$	$\tilde{R}_{F_{13}} =< \left[(0.088,\ 0.089,\ 0.09,\ 0.091)_{LR}; 0.75; 0.9\right] >$
$\tilde{R}_{B_7} =< \left[(0.008,\ 0.009,\ 0.010,\ 0.011)_{LR}; 0.6; 0.7\right] >$	$\tilde{R}_{H_1} =< \left[(0.029,\ 0.030,\ 0.001,\ 0.001)_{LR}; 0.77; 0.89\right] >$
$\tilde{R}_{B_8} =< \left[(0.011,\ 0.012,\ 0.001,\ 0.001)_{LR}; 0.7; 0.9\right] >$	$\tilde{R}_{H_2} =< \left[(0.011,\ 0.012,\ 0.001,\ 0.001)_{LR}; 0.57; 0.75\right] >$
$\tilde{R}_{B_9} =< \left[(0.039,\ 0.040,\ 0.001,\ 0.001)_{LR}; 0.6; 0.85\right] >$	$\tilde{R}_{H_3} =< \left[(0.029,\ 0.030,\ 0.001,\ 0.001)_{LR}; 0.7; 0.9\right] >$
$\tilde{R}_{B_{10}} =< \left[(0.001,\ 0.001,\ 0,0)_{LR}; 0.9; 0.95\right] >$	$\tilde{R}_{H_4} =< \left[(0.026,\ 0.027,\ 0.001,\ 0.001)_{LR}; 0.69; 0.77\right] >$
$\tilde{R}_{B_{11}} =< \left[(0.009,\ 0.010,\ 0.001,\ 0.001)_{LR}; 0.65; 0.8\right] >$	$\tilde{R}_{H_5} =< \left[(0.089,\ 0.09,\ 0.001,\ 0.001)_{LR}; 0.7; 0.8\right] >$
$\tilde{R}_{B_{12}} =< \left[(0.019,\ 0.020,\ 0.001,\ 0.001)_{LR}; 0.7; 0.85\right] >$	$\tilde{R}_{H_6} =< \left[(0.033,\ 0.034,\ 0.001,\ 0.001)_{LR}; 0.6; 0.8\right] >$
$\tilde{R}_{B_{13}} =< \left[(0.019,\ 0.020,\ 0.001,\ 0.001)_{LR}; 0.75; 0.95\right] >$	$\tilde{R}_{H_7} =< \left[(0.021,\ 0.022,\ 0.001,\ 0.001)_{LR}; 0.72; 0.88\right] >$
$\tilde{R}_{B_{14}} =< \left[(0.009,\ 0.010,\ 0.001,\ 0.001)_{LR}; 0.7; 0.9\right] >$	$\tilde{R}_{H_8} =< \left[(0.072,\ 0.073,\ 0.001,\ 0.001)_{LR}; 0.67; 0.91\right] >$
$\tilde{R}_{B_{15}} =< \left[(0.001,\ 0.001,\ 0,0)_{LR}; 0.74; 0.8\right] >$	$\tilde{R}_{H_9} =< \left[(0.001,\ 0.001,\ 0,0)_{LR}; 0.7; 0.9\right] >$
$\tilde{R}_{B_{16}} =< \left[(0.049,\ 0.05,\ 0.001,\ 0.001)_{LR}; 0.9; 0.95\right] >$	$\tilde{R}_{H_{10}} =< \left[(0.079,\ 0.08,\ 0.001,\ 0.001)_{LR}; 0.6; 0.7\right] >$
$\tilde{R}_{B_{17}} =< \left[(0.001,\ 0.001,\ 0,0)_{LR}; 0.7; 0.9\right] >$	$\tilde{R}_{J_1} =< \left[(0.001,\ 0.002,\ 0.001,\ 0.001)_{LR}; 0.67; 0.91\right] >$
$\tilde{R}_{B_{18}} =< \left[(0.009,\ 0.010,\ 0.001,\ 0.001)_{LR}; 0.6; 0.8\right] >$	$\tilde{R}_{J_2} =< \left[(0.029,\ 0.030,\ 0.001,\ 0.001)_{LR}; 0.72; 0.88\right] >$
$\tilde{R}_{D_1} =< \left[(0.069,\ 0.070,\ 0.001,\ 0.001)_{LR}; 0.69; 0.77\right] >$	$\tilde{R}_{J_3} =< \left[(0.001,\ 0.001,\ 0,0)_{LR}; 0.7; 0.9\right] >$
$\tilde{R}_{D_2} =< \left[(0.011,\ 0.012,\ 0.001,\ 0.001)_{LR}; 0.67; 0.91\right] >$	$\tilde{R}_{J_4} =< \left[(0.002,\ 0.003,\ 0.001,\ 0.001)_{LR}; 0.6; 0.8\right] >$
$\tilde{R}_{D_3} =< \left[(0.009,\ 0.010,\ 0.001,\ 0.001)_{LR}; 0.72; 0.88\right] >$	$\tilde{R}_{J_5} =< \left[(0.004,\ 0.005,\ 0.001,\ 0.001)_{LR}; 0.9; 0.95\right] >$
$\tilde{R}_{D_4} =< \left[(0.019,\ 0.020,\ 0.001,\ 0.001)_{LR}; 0.5; 0.7\right] >$	$\tilde{R}_{J_6} =< \left[(0.009,\ 0.010,\ 0.001,\ 0.001)_{LR}; 0.67; 0.91\right] >$
$\tilde{R}_{D_5} =< \left[(0.029,\ 0.030,\ 0.001,\ 0.001)_{LR}; 0.7; 0.9\right] >$	$\tilde{R}_{J_7} =< \left[(0.021,\ 0.022,\ 0.001,\ 0.001)_{LR}; 0.77; 0.89\right] >$
$\tilde{R}_{D_6} =< \left[(0.009,\ 0.010,\ 0.001,\ 0.001)_{LR}; 0.6; 0.8\right] >$	$\tilde{R}_{J_8} =< \left[(0.019,\ 0.020,\ 0.001,\ 0.001)_{LR}; 0.72; 0.88\right] >$
$\tilde{R}_{D_7} =< \left[(0.019,\ 0.020,\ 0.001,\ 0.001)_{LR}; 0.9; 0.95\right] >$	$\tilde{R}_{J_9} =< \left[(0.001,\ 0.001,\ 0,0)_{LR}; 0.69; 0.77\right] >$
$\tilde{R}_{D_8} =< \left[(0.049,\ 0.05,\ 0.001,\ 0.001)_{LR}; 0.67; 0.91\right] >$	$\tilde{R}_{J_{10}} =< \left[(0.001,\ 0.001,\ 0,0)_{LR}; 0.7; 0.9\right] >$
$\tilde{R}_{D_9} =< \left[(0.044,\ 0.045,\ 0.001,\ 0.001)_{LR}; 0.72; 0.88\right] >$	$\tilde{R}_{J_{11}} =< \left[(0.002,\ 0.003,\ 0.001,\ 0.001)_{LR}; 0.6; 0.8\right] >$
$\tilde{R}_{D_{10}} =< \left[(0.029,\ 0.030,\ 0.001,\ 0.001)_{LR}; 0.6; 0.7\right] >$	$\tilde{R}_{J_{12}} =< \left[(0.001,\ 0.001,\ 0,0)_{LR}; 0.5; 0.7\right] >$
$\tilde{R}_{D_{11}} =< \left[(0.009,\ 0.010,\ 0.001,\ 0.001)_{LR}; 0.69; 0.77\right] >$	$\tilde{R}_{L_1} =< \left[(0.009,\ 0.010,\ 0.001,\ 0.001)_{LR}; 0.67; 0.91\right] >$
$\tilde{R}_{D_{12}} =< \left[(0.009,\ 0.010,\ 0.001,\ 0.001)_{LR}; 0.6; 0.8\right] >$	$\tilde{R}_{L_2} =< \left[(0.019,\ 0.020,\ 0.001,\ 0.001)_{LR}; 0.72; 0.88\right] >$
$\tilde{R}_{D_{13}} =< \left[(0.002,\ 0.003,\ 0.001,\ 0.001)_{LR}; 0.7; 0.9\right] >$	$\tilde{R}_{L_3} =< \left[(0.039,\ 0.04,\ 0.001,\ 0.001)_{LR}; 0.9; 0.95\right] >$
$\tilde{R}_{D_{14}} =< \left[(0.079,\ 0.08,\ 0.001,\ 0.001)_{LR}; 0.67; 0.91\right] >$	$\tilde{R}_{L_4} =< \left[(0.019,\ 0.020,\ 0.001,\ 0.001)_{LR}; 0.77; 0.89\right] >$
$\tilde{R}_{F_1} =< \left[(0.019,\ 0.020,\ 0.001,\ 0.001)_{LR}; 0.6; 0.7\right] >$	$\tilde{R}_{L_5} =< \left[(0.044,\ 0.045,\ 0.001,\ 0.001)_{LR}; 0.6; 0.8\right] >$
$\tilde{R}_{F_2} =< \left[(0.029,\ 0.030,\ 0.001,\ 0.001)_{LR}; 0.72; 0.88\right] >$	$\tilde{R}_{U_1} =< \left[(0.029,\ 0.030,\ 0.001,\ 0.001)_{LR}; 0.67; 0.91\right] >$
$\tilde{R}_{F_3} =< \left[(0.001,\ 0.001,\ 0,0)_{LR}; 0.9; 0.95\right] >$	$\tilde{R}_{U_2} =< \left[(0.039,\ 0.04,\ 0.001,\ 0.001)_{LR}; 0.7; 0.9\right] >$
$\tilde{R}_{F_4} =< \left[(0.049,\ 0.05,\ 0.001,\ 0.001)_{LR}; 0.6; 0.8\right] >$	$\tilde{R}_{U_3} =< \left[(0.199,\ 0.2,\ 0.001,\ 0.001)_{LR}; 0.69; 0.77\right] >$
$\tilde{R}_{F_5} =< \left[(0.089,\ 0.09,\ 0.001,\ 0.001)_{LR}; 0.6; 0.7\right] >$	$\tilde{R}_{U_4} =< \left[(0.019,\ 0.020,\ 0.001,\ 0.001)_{LR}; 0.72; 0.88\right] >$
$\tilde{R}_{F_6} =< \left[(0.008,\ 0.009,\ 0.001,\ 0.001)_{LR}; 0.67; 0.91\right] >$	$\tilde{R}_{U_5} =< \left[(0.199,\ 0.2,\ 0.001,\ 0.001)_{LR}; 0.6; 0.8\right] >$
$\tilde{R}_{F_7} =< \left[(0.044,\ 0.045,\ 0.001,\ 0.001)_{LR}; 0.7; 0.9\right] >$	-

3.2. Experimental results

3.2.1. Traditional probability reliability

The traditional probability reliability or crisp reliability method are based on probabilistic approach assume failure probabilities as random variables with known probability distributions in order to incorporate the variation in the estimated values. If the available past failure data is insufficient then results shows a large variation or statistical inferences. In this paper the calculated reliability of a gas power plant by the traditional probability reliability method based on the data given in Table 2 (assuming $m = (m+n)/2; \alpha = 0, \beta = 0),$) and equation (i) is 0.8880 as shown in Figure 11.

3.2.2. Hong and Do' method [7]

In Hong and Do' approach,the fuzzy probabilities of different components are represented by L - R type flat fuzzy numbers with $L(x) = R(x) = e^{-x}$. Using equation (i), the data presented in Table 2 (assuming the values of truth membership function as 1). The fuzzy reliability $\tilde{R}$ of a gas power plant is:

$$\tilde{R} = (0.8844,\ 0.8917,\ 0.0078,\ 0.0069)_{LR}$$

The membership function representing the fuzzy reliability $\tilde{R}$ is shown in Figure 11. The most possible value of reliability of a gas power plant lies between 0.8844 and 0.8917. The membership values $\mu_{\tilde{R}}$(r)corresponding to different values of crisp reliability ‘r’ can be evaluated as follows:

$$\mu_{\tilde{R}}(r) = \begin{cases} L\left(\frac{0.8844-r}{0.0078}\right), & \mathrm{r} \le 0.8844 \\ 1 & , 0.8844 \le \mathrm{r} \le 0.8917 \\ \mathrm{R}\left(\frac{\mathrm{r}-0.8917}{0.0069}\right), & r \ge 0.8917 \end{cases} \tag{ii}$$

3.2.3. Kumar et al.'s method [16]

In this approach, the fuzzy probabilities of different components are represented by L - R type triangular vague set $L(x) = R(x) = e^{-x}$. Using equation (i), data presented in Table 2 (assuming, $m = \frac{m+n}{2}$) and arithmetic operations presented in [16] , the evaluated fuzzy reliability $\tilde{R}$ of a gas power plant is:

$$\tilde{R} =< [(0.8880,\ 0.0114,\ 0.0106)_{LR}; 0.5; 0.7] >$$

The membership function representing the fuzzy reliability $\tilde{R}$ is shown in Figure 11.The most possible value of reliability of a gas power plant is 0.8880 with the degree 0.5 of membership and degree 0.7 of complement non-membership. The membership $t_{\tilde{R}}(r)$ and complement of non-membership (1 - $f_{\text{-}R}$ (r)) corresponding to different values of crisp reliability ’ r’ can be evaluated as follows:

$$t_{\tilde{R}}(r) = \begin{cases} 0.5L\left(\frac{0.8880-r}{0.0114}\right), & r \le 0.8880 \\ 0.5, & r = 0.8880 \\ 0.5R\left(\frac{r-0.8880}{0.0106}\right), & r \ge 0.8880 \end{cases} \quad 1 - f_{\tilde{R}}(r) = \begin{cases} 0.7L\left(\frac{0.8880-r}{0.0114}\right), & r \le 0,8880 \\ 0.7, & r = 0,8880 \\ 0.7R\left(\frac{r-0.8880}{0.0106}\right), & r \ge 0.8880 \end{cases} \tag{iii}$$

3.2.4. Proposed approach

In this approach, the fuzzy probabilities of different components are represented by L- R type flat vague set L(x) = R(x) = e$^{\sim x}$. Using equation (i), arithmetic operation proposed in Section 2.2 and the data presented in Table 2, the evaluated fuzzy reliability $\widetilde{R}$ of a gas power plant is:

$$\tilde{R} =< [(0.8844,\ 0.8917,\ 0.0078,\ 0.0069)_{LR}; 0.5; 0.7] >$$

The membership function representing the fuzzy reliability $\widetilde{R}$ is shown in Figure 11. The most possible value of reliability of a gas power plant lies between 0.8844 and 0.8917 with the degree 0.5 of membership and degree 0.7 of complement of non-membership. The membership $t_{\widetilde{R}}(r)$ and complement of non-membership (l - $f_{\widetilde{R}}$ (r)) corresponding to different values of crisp reliability ’ r’ can be evaluated as follows:

$$t_{\tilde{R}}(r) = \begin{cases} 0.5L\left(\frac{0.8844-r}{0.0078}\right), & r \le 0.8844 \\ 0.5, & 0.8844 \le r \le 0.8917 \\ 0.5R\left(\frac{r-0.8917}{0.0069}\right), & r \ge 0.8917 \end{cases} \quad 1 - f_{\tilde{R}}(r) = \begin{cases} 0.7L\left(\frac{0.8844-r}{0.0078}\right), & r \le 0.8844 \\ 0.7, & 0.8844 \le r \le 0.8917 \\ 0.7R\left(\frac{r-0.8917}{0.0069}\right), & r \ge 0.8917 \end{cases} \tag{iv}$$

4. Comparison and discussion

The results obtained by using Traditional method, Hong and Do [12], Kumar et al. [15] and proposed approach for different membership values are shown in Table 3. If $t_{\widetilde{R}}(r)$ and $f_{\widetilde{R}}(r)$ are calculated for a particular value of reliability ' r', then the obtained results can be compared as follows:

i: In Crisp reliability method, the reliability of top event is equal to 0.8880 at all value of α, its means this method does not consider any vagueness present in data. This method is fit where the data is precise and certain, also it do not consider the confidence level of domain experts.

ii: In Hong and Do [12], for a particular value of crisp reliability ' r' if the membership value is α, then the non-membership value corresponding to same value of ' r' is $(1-\alpha)$. Therefore, it may be concluded that the value of reliability of the system is ' r' with the degree a of membership, degree $(1-\alpha)$ of non-membership and degree 0 of indeterminacy membership. For example, using Table 3 and equation (ii), it may be seen that the degree of membership and non-membership corresponding to crisp reliability $r = 0.8827$ are 0.8 and 0.2 respectively. There is no degree of indeterminacy membership that the value of reliability is 0.8827. Also, the most possible value of reliability of the system lies between 0.8844 and 0.8917. It means that the existing approach [12] cannot express the fuzziness under confirmable confidence level.

iii: In the Kumar et al. [15], let the value of $t_{\widetilde{R}}(r)$ for a particular value of crisp reliability ' r' is α and corresponding to the same value of ' r' the value of $f_{\widetilde{R}}(r)$ is β. Then on the basis of $t_{\widetilde{R}}(r)$ and $f_{\widetilde{R}}(r)$, it can be concluded that the value of reliability of the system be ' r' with the degree α of membership, degree of β non-membership and degree $(1-(\alpha-\beta))$ of indeterminacy membership. For example, using Table 3 and equation (iii), it can be seen that the degree of membership and non-membership corresponding to crisp reliability $r = 0.8827$ are 0.31 and 0.66 respectively. There is 0.03 degree of indeterminacy membership that the value of reliability is 0.8827. The most possible value of reliability of the system occurring at unique point (i.e. 0.8880). Therefore this approach is unable to express the vagueness in practical manner.

iv: In the proposed method, let the value of $t_{\widetilde{R}}(r)$ for a particular value of crisp reliability ' r' is α and corresponding to the same value of ' r' the value of $f_{\widetilde{R}}(r)$ is β. Then, on the basis of values of $t_{\widetilde{R}}(r)$ and $f_{\widetilde{R}}(r)$, it can be concluded that the value of reliability of the system be ' r' with the degree α of membership, degree β of non-membership and degree $(1-(\alpha-\beta))$ of indeterminacy membership. For example, using Table 3 and equation (iv), it can be seen that the degree of membership and non-membership corresponding to crisp reliability $r = 0.8827$ are 0.4 and 0.45 respectively. There is 0.15 degree of indeterminacy membership that the value of reliability is 0.8827 which is not considered in existing approach [12]. The most possible value of reliability of the system lies between 0.8844 and 0.8917. Therefore, this approach expresses the vagueness in more practical manner than existing approach [15]. The proposed approach overcomes the drawbacks and can cover the results of existing approaches [12, 15]. If $1-\beta=\alpha=1$, then the results will be same as that obtained by using existing approach [12] and if $m=\frac{m+n}{2}$, then the results will be same as that obtained by using existing approach [15].

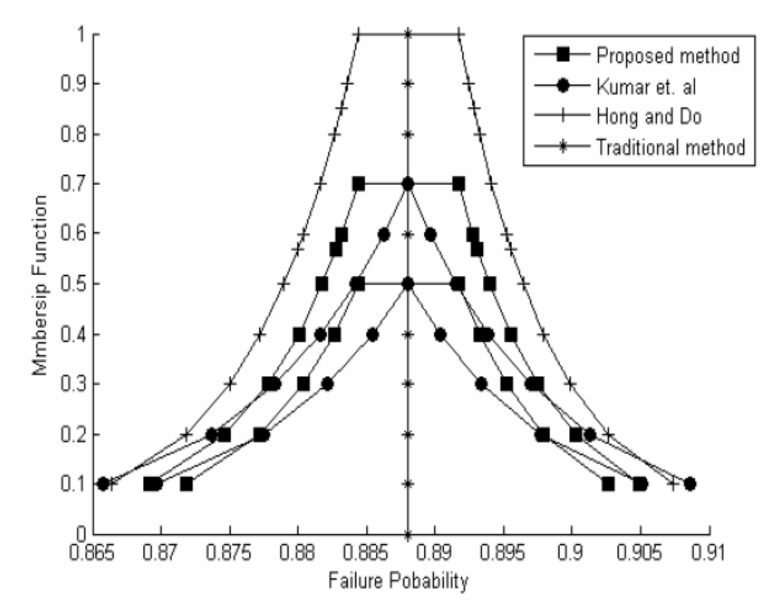

Figure 9.Membership function for top event of a gas power plant.

Table 3. Comparison of the results obtained by using existing and proposed methods corresponding to different membership values

α	**Crisp Reliability**	**Hong and Do[12]**				**Kumar et al.[15]**				
		m-α	m	n	$n+\beta$	m-α	$m—\alpha'$	m	$n+\beta'$	$n+\beta$
1.0	0.8880	0.8844	0.8844	0.8917	0.8917	–	–	–	–	–
0.9	0.8880	0.8836	0.8844	0.8917	0.8924	–	–	–	–	–
0.8	0.8880	0.8827	0.8844	0.8917	0.8932	–	–	–	–	–
0.7	0.8880	0.8816	0.8844	0.8917	0.8941	–	0.8880	0.8880	0.8880	–
0.6	0.8880	0.8804	0.8844	0.8917	0.8952	–	0.8862	0.8880	0.8896	–
0.5	0.8880	0.8790	0.8844	0.8917	0.8964	0.8880	0.8842	0.8880	0.8916	0.8880
0.4	0.8880	0.8773	0.8844	0.8917	0.8979	0.8855	0.8816	0.8880	0.8939	0.8904
0.3	0.8880	0.8750	0.8844	0.8917	0.8999	0.8822	0.8783	0.8880	0.8970	0.8934
0.2	0.8880	0.8718	0.8844	0.8917	0.9026	0.8776	0.8737	0.8880	0.9013	0.8977
0.1	0.8880	0.8664	0.8844	0.8917	0.9074	0.8697	0.8658	0.8880	0.9086	0.9051
0	0.8880	$—\infty$	0.8844	0.8917	∞	$—\infty$	$—\infty$	0.8880	∞	∞

α	**Crisp Reliability**	**Proposed Approach**					
		m-α	m-α'	m	n	$n+\beta'$	$n+\beta$
1.0	0.8880	–	–	–	–	–	–
0.9	0.8880	–	–	–	–	–	–
0.8	0.8880	–	–	–	–	–	–
0.7	0.8880	–	0.8844	0.8844	0.8917	0.8917	–
0.6	0.8880	–	0.8832	0.8844	0.8917	0.8927	–
0.5	0.8880	0.8844	0.8818	0.8844	0.8917	0.8940	0.8917
0.4	0.8880	0.8827	0.8800	0.8844	0.8917	0.8955	0.8932
0.3	0.8880	0.8804	0.8778	0.8844	0.8917	0.8975	0.8952
0.2	0.8880	0.8773	0.8746	0.8844	0.8917	0.9002	0.8979
0.1	0.8880	0.8718	0.8692	0.8844	0.8917	0.9049	0.9026
0	0.8880	$—\infty$	$—\infty$	0.8844	0.8917	∞	∞

5. Conclusion

The fault tree for gas power plant is constructed and due to uncertainty all the collected data are represented by L - R type vague sets. Furthermore, the minimal cut set approach is used to remove the repetition of the events from the expression for the top event and an expression is obtained in terms of minimal cut sets. Using the L - R type vague sets, T_w -based arithmetic operations on L - R type vague sets and collected data the fuzzy reliability of a gas power plant is evaluated and the obtained results are discussed. On the basis of obtained values of fuzzy reliability, it is concluded that the fuzzy reliability using vague set may express the real life situation.

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THE METHODS OF DISTRIBUTED AND DYNAMIC STATE ESTIMATION FOR MONITORING OF POWER SYSTEM OPERATING CONDITIONS*

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Abstract. Development of monitoring of energy power system (EPS) operating conditions requires update informative technologies. In the paper the modern methods of static and dynamic state estimation are suggested, which use synchronized phasor measurements along with traditional SCADA data. Such methods include the structural and functional decomposition of SE problem and forecasting of EPS operating conditions.

Keywords: Power System State Estimation, SCADA, PMU, WAMS, Distributed State Estimation, The Structural and Functional Decomposition of SE Problem, Forecasting of EPS Operating Conditions.

1. Introduction

The traditional system for monitoring of power system state includes devices intended to measure the required state variables and tools for their processing as well as systems for their storage and mapping. Until recently the measurements employed in the EPS state estimation were mainly the measurements received from SCADA (Supervisory Control And Data Acquisition) system. The SCADA systems are designed to receive and process data at a rate of once per second. At the same time there are delays in data delivery of several tens of seconds. In order to improve the reliability of data the state estimation methods are applied, which make it possible to filter random measurement errors, i.e. estimate them and calculate non-measured state variables. The disadvantages of SCADA systems in terms of energy problems are insufficient volume and low accuracy of measurements.

State estimation of modern large scale power systems that contain thousands of nodes of different voltage levels encounters the problems that concern inhomogeneity of the studied systems, large volume, irregularity, incompleteness and inaccuracy of data obtained from the measuring systems. This leads to bad conditionality of the problem solved, to slow convergence of the computational process and considerable distortion of state estimation and, as a result, to make a wrong decision in generation of control actions [1].

Besides, SCADA systems do not provide absolute synchronization of data because measurements are scanned successively. Non-simultaneous arrival of measurements is particularly noticeable when calculating subsystems that operate in parallel and have their own SCADA. The state variables calculated on the basis of such data lag behind the current state of EPS. Analysis and formation of control actions on the basis of delayed data is a reason for delayed response of control system to EPS behavior which results in overestimated requirements for static and dynamic stability margins, and decreases the overall efficiency of emergency control systems.

An essentially higher level of observability and controllability in EPS can be achieved owing to the WAMS (Wide-Area Measurement Systems) technology. Creation of the wide area systems of synchronized data with PMUs as basic measurement devices [2] enables power systems to both operate accurately and improve essentially the results of power system state estimation [3].

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The synchronized PMU data received from WAMS (voltage and current phasor measurements and their derivatives), distributed data processing on the basis of modern network technologies and decomposition methods of state estimation problem make it possible to essentially enhance the efficiency of computational procedure of state estimation for EPS with a multi-layer hierarchical structure.

Along with the improvement of algorithms for EPS state estimation and the increase of their speed, an important role in creating a system for monitoring the current state of EPS is also played by the algorithms of dynamic state estimation of EPS [4] and short-term forecasting of state variables [5] that are developed for the purposes of operation and emergency control of EPS but have not been paid sufficient attention to until now.

Due to the absence of short-term forecasting systems the analysis and generation of control actions are made on the basis of obsolete data with a delay from several tens of milliseconds to several tens of seconds. With the time required for response and decision making by dispatcher the real delay equals minutes, while monitoring and control problems require some advance estimation of system state.

In this paper the problems of distributed state estimation and forecasting the state variables of expected operating conditions are considered for development of power monitoring system.

2. The EPS state estimation problem and methods to solve it

The problem of EPS state estimation can be formulated as a problem of steady state calculation by the data of measured state variables and signals about the state of switching equipment.

Since the measurements $\bar{y}$ contain errors we calculate the estimates $\hat{y}$, that are the closest to the measured variables $\bar{y}$ in the sense of some criterion, and satisfy the electric circuit equations

$$w\left(y, z\right) = 0, \tag{1}$$

that relate measured y and unmeasured z state variables. Most frequently the sum of the least-weighted squares of estimate deviations from measurements is used as a criterion:

$$J\left(y\right) = \left(\bar{y} - \hat{y}\right) R_y^{-1} \left(\bar{y} - \hat{y}\right), \tag{2}$$

where R_y^{-1} — a diagonal matrix of weighting coefficients, R_y — a measurement error covariance matrix whose diagonal elements are equal to measurement variances: $r_{ii} = \sigma_i^2$.

To solve the state estimation problem we introduce the notion of state vector x. It has a dimension $2n - 1$ (where n is the number of nodes in the calculated scheme) including the magnitudes U and phase angles δ of voltages, i.e. $x = (\delta, U)$, excluding the fixed phase of a slack node. Such a state vector uniquely determines all the other state parameters. In this case equations (1) are represented by explicit dependences of measured and unmeasured variables on x:

$$y = y(x), \tag{3}$$

$$z = z(x). \tag{4}$$

Equations (3) are used to determine the components of state vector x by measured variables, and the SE problem is reduced for minimization of criterion (5)

$$J(x) = (\bar{y} - y(x))^{\mathrm{T}} R_y^{-1} (\bar{y} - y(x)), \tag{5}$$

i.e. to the calculation of the estimates of state vector $\hat{x}$. Then, equations (4) are used to calculate the estimates of unmeasured variables. This method is given in more detail in [6].

The test equation (TE) method was developed at ESI SB RAS [6, 7]. Test equations are the equations of electrical circuits that contain only measured state variables y:

$$w_k(y) = 0. \tag{6}$$

They can be obtained from the set of EPS steady state equations by excluding unmeasured variables z.

The substitution of the obtained measurements into the test equation results in discrepancies due to measurement errors. If the magnitude of TE discrepancy is higher than some threshold value d_i, i.e. the condition

$$|w_{ki}(\bar{y}_i)| > d_i \tag{7}$$

is met, then the measurements that belong to it are considered to have bad data. The value of d_i is determined by statistic properties of normal measurement errors that enter in this test equation. The algorithms for logical analysis have been developed to detect bad data among the measurements entering into the test equations with large discrepancies.

In this statement SE problem consists in minimization of objective function (2) with constraints (6) in the TE form.

3. Distributed state estimation

Distributed processing of data for decomposition of state estimation problems is an efficient method of solving problems for monitoring and forecasting operating conditions and for real-time and emergency control. This approach to state estimation is offered in the articles by the Russian scientists [8,9] and scientists from other countries [10-12] etc.

The basic algorithms of SE problem decomposition are based on division of the calculated scheme into subsystems by either boundary nodes or boundary branches [2]. Decomposition of the calculated scheme by boundary branches is used more often.

Decomposition algorithms of solving the SE problem by the test equation method.

Distributed SE includes the following main procedures:

1) decomposition of the entire calculated scheme into subsystems (local areas),

2) state estimation for each local area on the basis of available local area measurements,

3) solution of the coordination problem, i.e. calculation of the boundary variables and check of the boundary conditions. If the conditions are not met, the subsystems are recalculated with new values of boundary variables,

4) aggregation of calculation results for individual subsystems and transfer of aggregated data to the Control Center.

The decentralized approach utilizes the method of test equations (TE) and consists in the following [13]. For each of the subsystems we solve the SE problem, i.e. determine the minimum of the objective function (2)

$$\varphi_\nu = (\bar{y}_\nu - y_\nu)^T R_{y_\nu}^{-1} (\bar{y}_\nu - y_\nu) \tag{8}$$

at constraints in the form of a system of test equations

$$w_k\left(y_\nu, y_b\right) = 0$$

where v — the subsystem's number, y_b are measured boundary variables. The obtained estimates of the boundary variables are transferred to the upper level where the coordination problem is solved which consists in minimization of

$$\varphi_b = \left(\bar{y}_b - y_b\right)^T R_{y_b}^{-1} \left(\bar{y}_b - y_b\right) \tag{9}$$

at constraints in the form of test equations that include only boundary variables

$$w_k(y_b) = 0.$$

Problems (8) and (9) are solved iteratively until the required accuracy of estimates is achieved.

Use of PMUs for distributed state estimation. For decomposition of power system SE problem it is necessary to maintain accurate values of voltage magnitudes and phases at boundary nodes of subsystems for iteration-free solution of coordination problem. Placement of PMUs at boundary nodes makes it possible to considerably simplify the procedure of coordinating solutions for individual subsystems. With an optimal combination of physical and "calculated"

PMUs[1] at all boundary nodes of subsystems it is possible to determine voltage magnitudes and phases required to coordinate the solutions obtained for individual subsystems.

Installation of PMUs at boundary nodes allows one to fix boundary variables U and δ on the values measured with high accuracy.

When decomposition of the calculated scheme into subsystems is made by boundary branches a physical PMU is installed at one of the nodes of boundary branch, and a “calculated” PMU can be placed at the other end of the branch. In this case:

- the combination of measurements from physical and ”calculated” PMUs at an incident node ensures that boundary conditions in boundary branches are met,
- since PMU installed at a node allows one to obtain or calculate the measurements (pseudo-measurements) of power flows in all the branches adjacent to the node the boundary conditions (the relationships for power flows from the i-th subsystem to the j-th subsystem) will also be fulfilled.

In this case SE of separate subsystems can be calculated independently from each other, the iterative calculations on subsystems are not required.

For coordination of voltage phase angles received from local areas only one node with PMU measurement of phase angle is enough in each subsystem. Such node is appointed for subsystems as a slack node. PMU measurements coordinate the SE results obtained for separate subsystems.

When the calculated scheme is decomposed into subsystems by boundary branches a node at one end of the boundary branch in which PMU is installed can be chosen as a slack node. In spite of the fact that the “calculated” PMU with exact voltage phasor can be obtained for an incident node of the boundary branch it is undesirable to use this very node as a slack node of the second subsystem [14]. A more appropriate approach is installation of physical PMUs at slack nodes of each subsystem.

Bad data detection in telemetry, or validation of measurements, is one of the most important problems in EPS state estimation. In this work bad data detection is based on the test equation method. This method makes it possible to carry out validation of information prior to solving the SE problem. Solving the problem of state estimation for EPS with low redundancy of measurements we face the problem of validating the critical measurements and critical sets, which are defined in [15]. It is impossible to detect uniquely gross errors in these measurements. One of possible approaches to solution of this problem is the use of PMU measurements. Optimal placement of PMU increases the redundancy of SCADA measurements and eliminates critical measurements and critical sets, i.e. allows detection of all bad data in measurements.

When calculating simultaneously operating subsystems that have SCADA systems for collection and processing of telemetry, inaccurate synchronization of data in boundary regions of subsystems can cause interacting and, often, even conforming bad data, which considerably complicates the procedure of their processing and can affect the convergence of state estimation.

Accurately synchronized measurements provided by PMU placed near boundary nodes essentially increase the redundancy of measurements and efficiency of methods for detection of bad data in boundary regions.

A hierarchical algorithm of distributed SE has been developed for state estimation. It employs the structural decomposition of problem, i.e. division of the studied system into subsystems, and the functional decomposition which is made in accordance with the problems solved while estimating power system state: bad data detection, state estimation proper on the basis of squared and non-squared criteria.

Algorithm of structural decomposition using test equations.

To calculate large inhomogeneous schemes the authors propose a method of dividing the calculated scheme with respect to voltage levels [16]. This method decreases essentially a negative

[1]The voltage magnitude and phase at a neighboring node with PMU which are calculated on the base of the measurements received from the PMU. The accuracy of measurements of “calculated” PMU virtually equals the accuracy of measurements received from the physical PMU [2].

impact of the calculated scheme and telemetry inhomogeneity when subsystems of one voltage class are calculated but it inevitably leads to a large number of boundary nodes for complex schemes. Therefore, a two-stage algorithm is proposed for decomposition of the calculated scheme into subsystems [17].

At the first stage the scheme is divided into rather large areas with minimum number of tie lines and boundary nodes. This decomposition can be made on the basis of administrative division, for example, the entire scheme of Russia's UES is decomposed into regional power subsystems of large regions in the country that operate in parallel or it can be decomposed artificially into separate areas by special algorithms [18].

PMUs are placed at the boundary nodes of the areas. Highly accurate measurements obtained from PMU make it possible to register the values of magnitudes and phases of nodal voltages at the boundary nodes and make calculations for the areas in parallel.

At the second stage the calculated scheme of each area in turn is divided into subsystems that correspond to the levels of nodal voltages. The calculations start with the subsystem of the highest voltage level (750-500 kV). Normally this part of the scheme is well provided with highly accurate telemetry and contains a basic node. Then the calculations are made successively for the rest of the subsystems. The subsystems are ranked by voltage levels (220 kV, 110 kV, etc.). Every time the node bordering the subsystem of higher voltage level is chosen as a basic one.

After the calculation of the low level subsystems a coordination problem is solved for all areas. In this case boundary conditions [9] are met automatically, and the coordination problem implies calculation of nodal injections at the boundary nodes on the basis of power flow estimates obtained for each area .

The functional decomposition of the SE problem is performed in accordance with the problems solved within state estimation. The main of them are: analysis of network topology; analysis of observability; analysis of bad data; calculation of estimates and steady state by the estimates obtained. The current calculated scheme is formed for the entire scheme. Bad data detection class before solving the state estimation problem and calculation of estimates and steady state is performed by the test equation technique for each subsystem of a certain voltage [3].

State estimation is made by two criteria: the method of weighted least squares and the robust criterion that allows the estimates to be obtained and bad data to be suppressed simultaneously.

Interaction of problems. The criterion of EPS state estimation is selected depending on the solution to the a priori bad data detection problem. If bad data are detected or absent, which is indicated by a low value of discrepancies when checking condition (7) for all test equations, the criterion of weighted least squares is selected. When it is impossible to identify bad data, the robust criterion of SE with search of the bases for their suppression is chosen.

4. Study case

The calculations of all subsystems and comparison of their results with the reference state obtained in calculation of the full scheme are presented below (Fig.1).

Nodes with PMU: 2, 3, 8, 11, 14, 15, 16, 17, 19, nodes with "calculated" PMU: 1, 4, 5, 6, 7, 9, 10, 12, 13, 18. Branch 3–13 is tripped.

Node 2 is the slack node of the full scheme and of the subsystem I.

Results of calculations are presented in the tables 1-4.

The value of objective function (2) at the solution point is an important index of the quality of SE results (table 4).

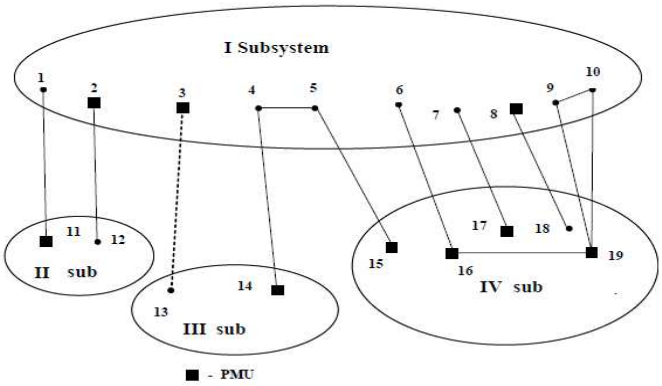

Figure 1. Real EPS scheme (328 nodes).

Table 1. Calculation of estimates at the slack node.

Node 2				
	U	δ	P_i	Q_i
Full scheme	755.7	6.7	678	77
Scheme of Subsystem I	755.7	6.7	678	76

Table 2. Calculation of estimates at boundary nodes.

Node	Full scheme			Subsystem I		
	U, kV	δ, degree	Transit or P_i, Q_i	U, kV	δ, degree	Transit or P_i, Q_i
1	331.8	4.7	transit	331.8	4.7	transit
4	509.2	4	transit	509.2	4	transit
5	526.2	3.1	transit	526.2	3.1	transit
6	519	3.6	transit	519	3.6	transit
7	502.3	6.6	transit	502.3	6.6	transit
8	512.7	7.1	$P_i = 210$ MW $Q_i = -523$ MVAR	512.7	7.1	$P_i = 192$ MW $Q_i = -514$ MVAR
9	507	1.9	transit	507	1.9	transit
10	510.5	0.8	transit	510.5	0.8	transit

Table 3. Calculation of estimates in boundary branches.

Branch	Full scheme				Subsystem I			
	P_{ij}	Q_{ij}	P_{ji}	Q_{ji}	P_{ij}	Q_{ij}	P_{ji}	Q_{ji}
1-11	146	-65	-145	36	146	-65	-145	36
2-12	34	-393	-34	-446	34	-393	-34	-446
4-14	490	-133	-485	-2	490	-133	-485	-2
5-15	-42	-44	42	-206	-42	-44	42	-206
6-16	67	-150	-66	-329	67	-150	-66	-329
7-17	-288	-234	293	-207	-288	-234	293	-207
8-18	171	-277	-170	-94	171	-277	-170	-94
9-19	-467	-97	470	-21	-467	-97	470	-21
10-19	-380	-99	383	-113	-380	-99	383	-113

Table 4. Value of the objective function.

Objective function	With PMU	Without PMU
φ_Σ	112346	151141
φ_P	94075	136660
φ_Q	12022	6956
φ_U	6248	7524

As it is shown in the table 4 the objective function of SE with using PMU is considerably less the objective function of SE without PMU.

5. Forecasting of the EPS operating conditions

Static state estimation processes one snapshot of SCADA (and PMU) measurements. Dynamic SE makes it possible to take into account the interrelation among state variables changing in time. The Kalman filter is used for dynamic SE. It gives the optimal estimation of EPS state in real time on the basis of measurements.

For the formation of the Kalman filter a system with 2 types of equations is constructed:

- the first type is a dynamic model $x(t)$,
- the other one is the dependence of measurements $\bar{y}$ on state vector x.

$$x_{k+1} = F_k x_k + \xi_{F_k}, \tag{10}$$

$$y_k = H_k x_k + \xi_{y_k}. \tag{11}$$

where ξ_{F_k} — the model noise, $M\left(\xi_{F_k}\right) = 0$, $cov\left(\xi_{F_k}\right) = M\left(\xi_{F_k}\xi_{F_k}^T\right) = \sigma_{F_k}^2$, $\quad \xi_{F_k} \in N\left(0, \sigma_{F_k}^2\right)$, $\sigma_{F_k}^2$ — the noise variance of dynamic model, F_k — a matrix of transition from one EPS state to another, H_k — Jacobian matrix.

After some manipulations of equations (10), (11) the covariance matrix of forecast errors can be obtained:

$$M_{k+1} = F_k P_k F_k + W_{F_{k+1}},$$

where $W_{F_{k+1}}$ — the noise variance of dynamic model matrix.

Objective function of dynamic state estimation looks as follows:

$$J(x) = \left(\bar{y} - y(x)\right)^{\mathrm{T}} R_y^{-1} \left(\bar{y} - y(x)\right) + \left(\bar{x} - x\right)^T * M^{-1} * \left(\bar{x} - x\right),$$

where $\bar{x}$ — measurements or pseudo measurements of state vector components.

In the problem of dynamic SE the components of state vector are considered as measurements if they are measured and as pseudo measurements if they are taken from the SE of the previous snapshot. In the objective function they are represented by different terms. For weighting coefficients for the second term we use the inverse matrix of the covariance matrix (M^{-1}), which makes it possible to take into account the accuracy of estimates obtained at the previous time instants.

Due to nonlinear dependence $y(x)$, the problem is solved iteratively by Newton's method. The initial conditions for each cycle are state estimation of system (values of state vector components) and covariance matrix which characterizes the estimation error. The algorithm processes newly coming measurement vectors by taking into account the measurement errors, and specifies the initial conditions. The adjusted initial conditions are the filter output data.

Dynamic state estimation is performed correctly after the Kalman filter tuning. The filter tuning implies stabilization of diagonal elements of the covariance matrix of forecast errors M.

For calculation of the covariance matrix of forecast errors the matrix of transition F is assumed to be a unit matrix.

Forecasting of all state vector components some time ahead makes it possible to forecast the values of all state variables. Forecasting of state vector components is considered as dynamic state estimation if there are no new measurements.

Creation of a database

In order to solve the stated problem we create a virtual database of measurement snapshots. Each snapshot is created in the following way: at a certain load value the steady state is calculated. Then the errors are generated by random number generator and superimposed on measured state variables. The values of measurements are calculated according to the expression:

$$y_{simul} = y_{ss} + x_{rand}\sqrt{\sigma^2},$$

where σ^2 — a variance of measurement errors, $x_{rand} \to N(0, 1)$, y_{ss} — a steady state variable. Calculated measurement values are called a snapshot and are initial data for solving the problem of dynamic state estimation. Fig. 2 presents the forecast values of voltage magnitude and phase measurement.

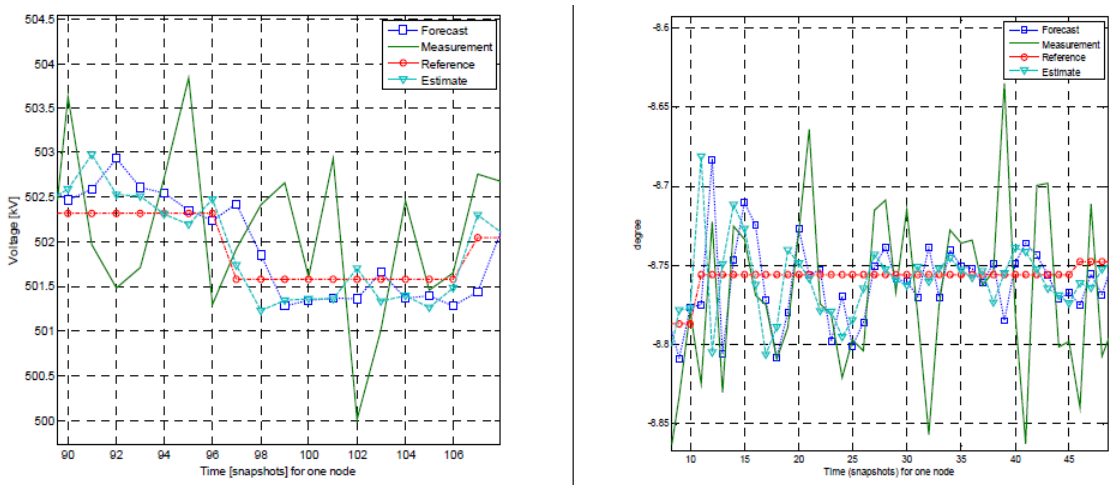

Figure 2. Forecasting the state vector component.

Table 5 (column 2) presents average errors in forecasting that were calculated in 200 snapshots in accordance with:

$$err = \frac{1}{k}\sum_{1}^{k}(|\tilde{x}| - |\hat{x}|),$$

where $\bar{x}$ — the measurement of state vector component, $\hat{x}$ — the estimate, $\tilde{x}$ — the forecast, k — the number of snapshots. Table 5 (column 3) presents average errors in forecasting in %.

Table 5. Average errors in forecasting state vector components.

Component	Average errors in forecast	
	kV, degrees	%
U	0.83	0.24
δ	0.004	0.36

Analysis of Fig.2 and table 5 shows that under the considered conditions the forecast is made with high accuracy.

6. Conclusion

1. Currently there is a need for development of a system for wide area monitoring in Russia. The problems of distributed static and dynamic state estimation and forecasting of the EPS current state and control are the basic procedures of this system.

2. The algorithms of distributed robust state estimation of large-scale power systems were developed on the basis of test equation method, new data sources (PMU data), structural and functional decomposition.

3. The use of synchronized highly accurate phasor measurements provided by PMUs makes it possible to solve certain problems arising in the SE problem decomposition:

1) PMU placement at boundary nodes considerably simplifies the procedure of coordinating solutions for individual subsystems and does not require iterative calculations by subsystems;

2) assigning the nodes with PMU as the slack nodes of subsystems provides coordination of voltage phase angles in subsystem calculations;

3) measurements from PMUs placed in the vicinity of boundary nodes essentially enhance the efficiency of bad data detection in boundary regions and improve the accuracy of obtained estimates.

4. Dynamic state estimation with application of the Kalman filter can be used to forecast the EPS state variables for a short period of time. Regular tuning the filter improves the forecast quality. The better the accuracy of measurements, the better the forecast.

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TRANSITIONAL REACTANCES OF CAPACITOR AT SWITCHING PROCESSES

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Abstract. Concept of transitional reactance of capacitor at high-frequency switching processes was considered in the article. Extreme condition for modulus of transitional reactance was found. There were got and presented graphs of transitional reactance against natural frequency of switched circuit and initial phase angle. The results obtained were also presented in the table.

Keywords: Transitional Reactance, Capacitor, Natural Frequency.

1. Introduction

The classical concept of reactance is based on its representation as a ratio of rms (root mean square) of voltage to current rms [1]. Such a concept concerned to steady-state regime of electrical circuit and covered cases of purely harmonic voltages and currents. For lots of practical applications with non-harmonic (non-sinusoidal) voltages and currents this concept is not sufficient.

As it was noticed by prof. Krug (see [2]) real values of reactance of capacitor and inductive coil while applying non-sinusoidal voltages are differed from values determined by the above-minded way. Degree of change the reactance under consideration conditioned by the anharmonicity of voltages and currents was researched in [4]. The similar approach had been used in [3].

In general the concept of transitional reactance is already known and widely used for synchronous and asynchronous electric machines at calculation short-circuit currents [7]. Let us consider this definition for capacitor (capacitor banks).

2. Exstremum search

As it is known from [5] the reactance of capacitor at high-frequency transient may be presented by the following way:

$$x_C = x_\omega H_C, \tag{1}$$

where x_ω is reactance of capacitor at the voltage source frequency, H_c is a coefficient of reactance rate change which in accordance with [5] is equal to

$$X_C = X_\omega \frac{1}{K}\sqrt{\frac{\cos^2\psi + K^2(1+\sin^2\psi)}{1+K^2\sin^2\psi+\cos^2\psi}}, \tag{2}$$

where ψ is the initial phase angle, k is a ratio of free frequency to the voltage source frequency.

Let us now determine a derivative of reactance (1) by the initial phase angle ψ. We can consistently write:

$$\frac{\partial x_C}{\partial\psi} = x_\omega \frac{\partial H_C}{\partial\psi},$$

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$$\frac{\partial H_C}{\partial \psi} = \frac{1}{2k}\sqrt{\frac{1+k^2\sin^2\psi+\cos^2\psi}{\cos^2\psi+k^2(1+\sin^2\psi)}}\cdot\frac{\partial}{\partial\psi}\left[\frac{\cos^2\psi+k^2(1+\sin^2\psi)}{1+k^2\sin^2\psi+\cos^2\psi}\right]. \tag{3}$$

Accept the following denotations:

$$f_1 = \cos^2\psi + k^2(1+\sin^2\psi), f_2 = 1+k^2\sin^2\psi+\cos^2\psi. \tag{4}$$

Then applying the known rule on derivative of ratio [6] we get

$$\frac{\partial}{\partial\psi}\left[\frac{\cos^2\psi+k^2(1+\sin^2\psi)}{1+k^2\sin^2\psi+\cos^2\psi}\right] = \frac{f_1' f_2 - f_1 f_2'}{f_2^2}. \tag{5}$$

Differentiate both (4) expressions:

$$\frac{\partial f_1}{\partial\psi} = -\sin 2\psi + k^2\sin 2\psi = (k^2-1)\sin 2\psi, \tag{6}$$

$$\frac{\partial f_2}{\partial\psi} = k^2\sin 2\psi - \sin 2\psi = (k^2-1)\sin 2\psi. \tag{7}$$

Taking into account expressions (6) and (7) in the (5) convention we can write

$$\frac{\partial}{\partial\psi}\frac{f_1}{f_2} = \frac{f_1'(f_2-f_1)}{f_2^2}. \tag{8}$$

Since

$$f_1 - f_2 = 1 - k^2,$$

then

$$\frac{\partial}{\partial\psi}\left[\frac{\cos^2\psi+k^2(1+\sin^2\psi)}{1+k^2\sin^2\psi+\cos^2\psi}\right] = \frac{(k^2-1)^2\sin 2\psi}{(1+k^2\sin^2\psi+\cos^2\psi)}.$$

For the derivative under consideration we can finally get the following expression:

$$\frac{\partial H_C}{\partial \psi} = \frac{1}{2k}\sqrt{\frac{1+k^2\sin^2\psi+\cos^2\psi}{\cos^2\psi+k^2(1+\sin^2\psi)}}\cdot\frac{(k^2-1)^2\sin 2\psi}{(1+k^2\sin^2\psi+\cos^2\psi)^2} \tag{9}$$

or

$$\frac{\partial H_C}{\partial \psi} = \frac{1}{2k}\cdot\frac{(k^2-1)^2\sin 2\psi}{\left[\cos^2\psi+k^2(1+\sin^2\psi)\right]^{1/2}\left(1+k^2\sin^2\psi+\cos^2\psi\right)^{3/2}}. \tag{10}$$

As it is seen from the obtained expression (10) the extremal values of the H_c coefficient take place at $k^2-1=0$ or $\sin 2\psi = 0$.

The first of obtained conditions means an equality of the voltage source frequency to the natural frequency of switched circuit i.e. it is concerned to the resonance case. For the considered case of series contour it is a voltage resonance [1]. For the capacitor banks of typical jet powers and transformers (and autotransformers) they are connected to this case is not possible. Subsequently, for the capacitor banks of power systems the extremal values of transitional capacitive reactance take place at Ψ=*0* and Ψ=*π/2*.

3. Results

The results of calculation the value of H_C against k (the very left column) and Ψ (the very upper column) are presented in the following table.

Table 1.

	0	$\pi/6$	$\pi/4$	$\pi/3$	$\pi/2$	$2\pi/3$
1	1.0	1.0	1.0	1.0	1.0	1.0
2	0.7906	0.723	0.6814	0.653	0.6325	0.653
3	0.7454	0.5774	0.5092	0.4714	0.4472	0.4714
4	0.7289	0.4749	0.4015	0.365	0.343	0.365
5	0.7211	0.4	0.3295	0.2966	0.2774	0.2966
6	0.7169	0.3438	0.2786	0.2494	0.2325	0.2494
7	0.7143	0.3006	0.241	0.2149	0.2	0.2149
8	0.7126	0.2666	0.2122	0.1887	0.1754	0.1887
9	0.7115	0.2392	0.1894	0.1682	0.1562	0.1682
10	0.7106	0.2168	0.1709	0.1516	0.1407	0.1516
11	0.71	0.1981	0.1558	0.138	0.128	0.138
12	0.7096	0.1823	0.143	0.1266	0.1174	0.1266
13	0.7092	0.1688	0.1322	0.117	0.1085	0.117
14	0.7089	0.1572	0.1229	0.1087	0.1008	0.1087
15	0.7087	0.147	0.1148	0.1015	0.09407	0.1015
17	0.7083	0.1301	0.1014	0.08962	0.08305	0.08962
20	0.708	0.1109	0.08632	0.07623	0.07062	0.07623

The curves of dependence of transitional capacitive reactance's rate of change against initial phase angle for different values of k (and indirectly the free frequency) are presented in the Fig.1-4. As it is seen from the presented figures the extreme value at $\Psi=\pi/2$ is the minimum one, at $\Psi=\pi/2$ it is taken place the greatest value of k. Another result obtained is the decreasing of transitional reactance while free frequency is increasing and initial phase angle is constant.

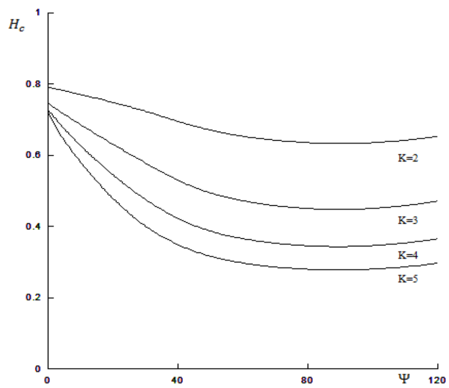

Figure 1. The dependence of transitional reactance on initial phase angle for k = 2,3,4,5.

We can also note that increasing of k leads to concentrating of all the curves' beginnings i.e. values of reactance at $\Psi=0$ in the some point on the vertical axe. Analyzing the graphs obtained and expressions concerned we can state that this point is approximately corresponds to 0,707 i.e. one divided by square root of 2.

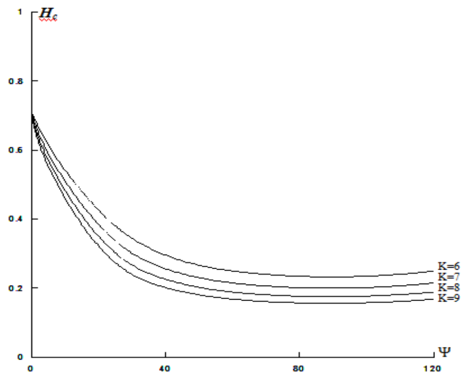

Figure 2. The dependence of transitional reactance on initial phase angle for k = 6,7,8,9.

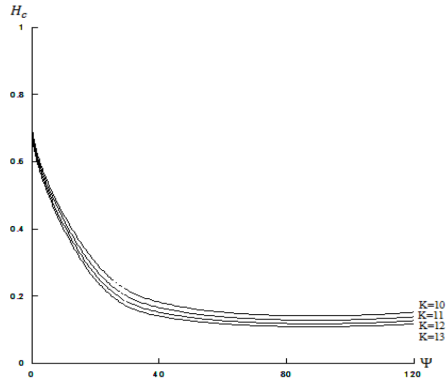

Figure 3. The dependence of transitional reactance on initial phase angle for k = 10,11,12,13.

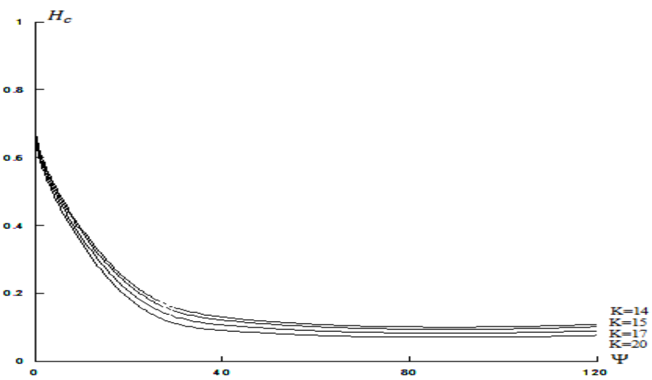

Figure 4. The dependence of transitional reactance on initial phase angle for k = 14,15,17,20.

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Scope of the Journal

The journal is initially planned to be published two times in a year and the solution of important problems on power engineering will be reflected in it. The main purpose of journal is the publication of high-level articles dedicated to electric power systems, power stations, substations and their main equipments, electrotechnical complexes, automation and management means, the development of alternative energy sources and their activity.

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