The Energy Router Based on a Solid-State High-Frequency Transformer

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Abstract— **This paper presents the envisioned next generation power distribution system architecture, the so called FREEDM system. The presented system enables the plug-and-play of distributed renewable energy resources and distributed energy storage devices, therefore functions as the "energy internet". The recent technical developments are summarized in this paper, with emphasis on the distributed grid intelligence, solid state transformer, DC microgrid, and fault isolation device. It is demonstrated that the FREEDM system is a highly attractive candidate for the future power distribution system.**

Keywords— smart grid; distributed generation; energy storage; solid state transformer

I. Introduction

The modern energy market requires the use of more sophisticated and complex electric power systems that provide not only more efficient, but also environmentally safe production and distribution of electrical energy. Universal computerization, "digitalization" and the widespread use of networked IT technologies are having an increasing impact on the functions and construction of the developed systems for managing electric power systems and electrical equipment. Today it is not enough to display the results of measurements of the device parameters on the monitor screen, but it is required to provide remote monitoring and supervisory control of it using local area networks (LANs) or the Internet [1 - 5].

This is simply implemented by converting control applications into HTML documents that can be published on a LAN or the Internet. In this case, the controller or computer connected to the LAN through a standard input / output device becomes a primary data server, and remote computers play the role of clients, and clients can use the usual "office" tools of standard web browsers. Almost all top-level software packages SCADA / HMI, widely used today for the creation of systems for power system management and technological automation, have standard components that simply implement the publication of such applications.

High level of reliability and survivability of LAN, maintenance of workability in case of failure of a part of equipment or connecting lines, automatic adaptation to the conditions of use, availability and low cost of equipment for their implementation ensure ease of use, meet stringent requirements for reliability of power systems management systems. Flexibility, guaranteed delivery of messages, development and implementation of algorithms for adapting the routing of information packets to the current state of the network led to attempts to implement the basic principles of Internet information networks in the electric power industry, the creation of Smart Grids and Energy Internet.

At the same time, the simplicity of implementing systems for monitoring, measuring and managing electric power systems with the help of information technology, the convenience of using them rely on enthusiasm and long-term development of programmers, mathematicians, circuit engineers, and specialists in the field of microelectronics. In order for electric networks to work on the principles of the "Energy Internet", it is required to create radically new universal electric and electronic devices and devices that allow creating active-adaptive energy electric networks. This means that the electrical networks must have electronic systems for diagnostics, control and technological automation with programmatic control, technical devices that allow to flexibly change the topology of the network and the directions of electric power flows, instantly disconnect large short-circuit currents, measure and take into account the energy consumption, provide the consumer voltage quality and type of current.

Only such electric networks will be able to combine distributed generation, heterogeneous sources of electric energy, devices for accumulation, transmission and consumption of electric energy. It is also necessary to automatically control the flow of electrical energy with simultaneous control of the quality of electrical energy, monitoring and evaluation of the status of network elements in various modes of operation in real time, remote control of active network elements and electrical installations of consumers, rapid change in network topology, increase of reliability of power supply, etc. Only such electric networks will enable any consumer to work on the market by choosing the best, in his opinion, generating company.

By analogy with LAN, where the main "network-forming" devices are concentrators, switches, bridges and routers, i.e. structuring switching equipment that allows managing information flows, it can be argued that the basis of the "Energy Internet" should be universal multifunctional devices that combine the functions of conversion, switching and changing the direction of electrical energy flows - "power routers" - power routers with software control connected via communication networks to the control centers of electric networks. In the existing electrical networks, these functions

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are still performed by switches, disconnectors, reclosers and transformers, most often with manual control.

"Weak link" of the structure of existing electrical networks are power transformers, since they cannot transform a constant or current of increased frequency, are poorly controlled and do not provide the quality of voltage necessary for the consumer. They have optimal parameters only at a constant load factor, do not provide protection of the consumer against various types of interference and overvoltage. Their design and theory have been known for more than a hundred years and, as a result of evolutionary changes, are practically brought to perfection. Today, the main trend in improving the design of new power transformers is to reduce the cost of production and operation, which often contradicts each other - on the one hand, a cheaper construction is required, and on the other, the use of more expensive technologies to improve quality and reduce operating costs.

Combine with power transformers energy sources with completely different characteristics: from ultra-high voltage AC and DC networks to a gasoline generator or solar battery for individual use is possible only with the help of additional sophisticated devices for each type of equipment. Meanwhile, it is believed that such an association will allow against the background of obsolescence and breakdown of distribution network equipment, increase in consumption, and improve the profitability of networks. The reduce losses in the transmission of electrical energy and the risk of system accidents, improve the reliability of energy supply, and optimize and allocate generation and consumption in Power grid will reduce the need for large-scale capital expenditures for new substations and transmission lines.

The experience of past system accidents on high-capacity power networks that caused severe consequences, when large cities - New York, Rome, Helsinki, London, Athens, Moscow - were deprived of electricity for a long time, and therefore water, sewerage, gas, electric transport, lifts and Etc., confirms this. The disadvantages of power transformers are also relatively low energy efficiency and the complexity of voltage stabilization in consumers. The latter is usually accomplished by switching the tapping of the windings by switching them with the transformer disconnected (switching without excitation - SWE), which causes interruptions in the power supply, or voltage regulators under load (RPN) of electromechanical or electronic types. RPN electromechanical type operate at high speeds of moving parts, which causes mechanical shocks during their operation, imposes strict requirements on the materials of these parts and reduces the reliability of work. Therefore, electromechanical on-load tap-changers are gradually replaced by electronic ones usually performed on photothyristors.

The energy efficiency of power transformers can be improved by optimizing the load factor (by optimizing the connection schemes of consumers), increasing the load power factor (by compensating or reducing the reactive power of consumers), reducing the idling loss power (losses in the magnetic circuit), and reducing the power of short-circuit losses (winding losses).

The first two parameters depend on consumers and are optimized by organizational measures, for example, by setting tariffs that depend on the time of day, imposing penalties, etc., or by technical measures, for example, by forcing consumers to switch off / connect and installing reactive power compensators. The second two parameters are optimized by improving the parameters of the transformer itself, but, since its design is already optimal, require the use of new materials for its manufacture.

For example, the use of amorphous (nanocrystalline) magnetic cores in new designs of transformers makes it possible to reduce idling losses by five or more times. Magnetic wire from an amorphous alloy is somewhat more expensive (by 25-40%) of a magnetic core made of electrical steel, which is explained by the higher price of the amorphous alloys themselves and the complexity of the process of manufacturing it. Typically, such a magnetic core is a folded one or otherwise thin ribbon, i. e. has a twisted construction that complicates its manufacturing as the size grows and limits the use in power transformers of high power.

A decrease in the power of short-circuit losses can be achieved, for example, by using windings made from high-temperature superconducting materials or from a special multiwire cable, with measures to eliminate the unevenness of the electric field caused by the stranded wires. This makes it possible to reduce the active and reactive resistance of the windings, to ensure a low dependence of the output voltage on the load current and to increase the overload capacity of the transformers, but leads to an increase in the cost of the transformer construction, since it requires an additional cooling system and more complex components.

There is another way to increase the energy efficiency of the transformer - switching to a higher conversion frequency, which theoretically allows, with the same transmitted power, in proportion to the increase in frequency in the cube, to reduce the volume of the transformer magnetic circuit, the length of the live parts of the windings and reduce energy losses. The choice of a particular conversion frequency is rather complicated, depends on many factors, and it is impossible to consider it within the framework of this article. To obtain an increased conversion frequency, devices that have long been known in power electronics-the rectifier and the inverter-are used (Fig. 1).

II. Solid State Transformer

A device combining rectifiers, inverters and a high-frequency transformer was called the Solid State Transformer. The methods of power electronics make it relatively easy to obtain a smooth adjustment of the output voltage of such a device and to ensure its quality, and have long been used in uninterruptible power supplies (UPSs) for the creation of systems of guaranteed power supplies. If the inverters and rectifiers are made on fully controlled keys with two-way conductivity (synchronous rectifier / inverter), then the energy flow both in the forward and reverse direction and regulation (stabilization) of the output voltage is relatively simple (Fig. 2, 3).

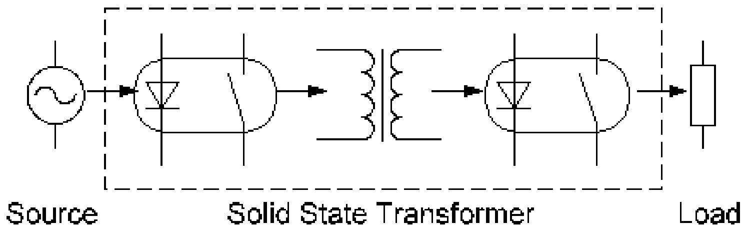

Fig. 1. Structure of high-frequency voltage converter - solid-state transformer

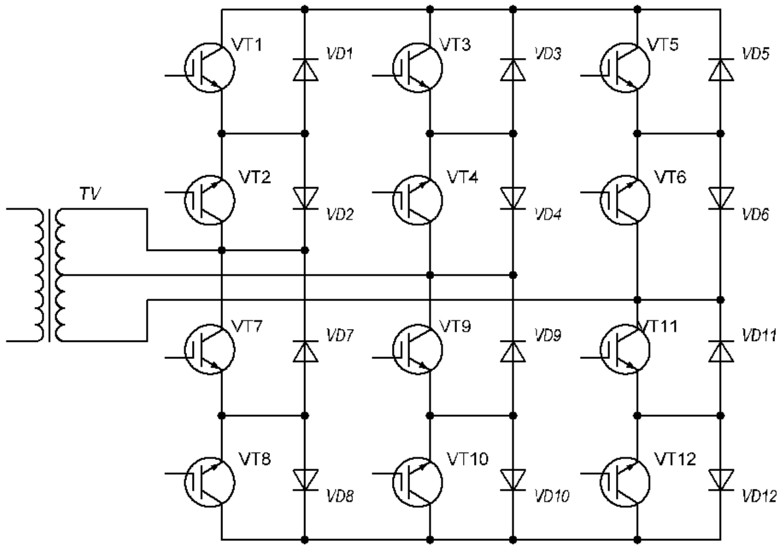

Fig. 2. The structure of the power part of a high-frequency bi-directional voltage converter with a DC link

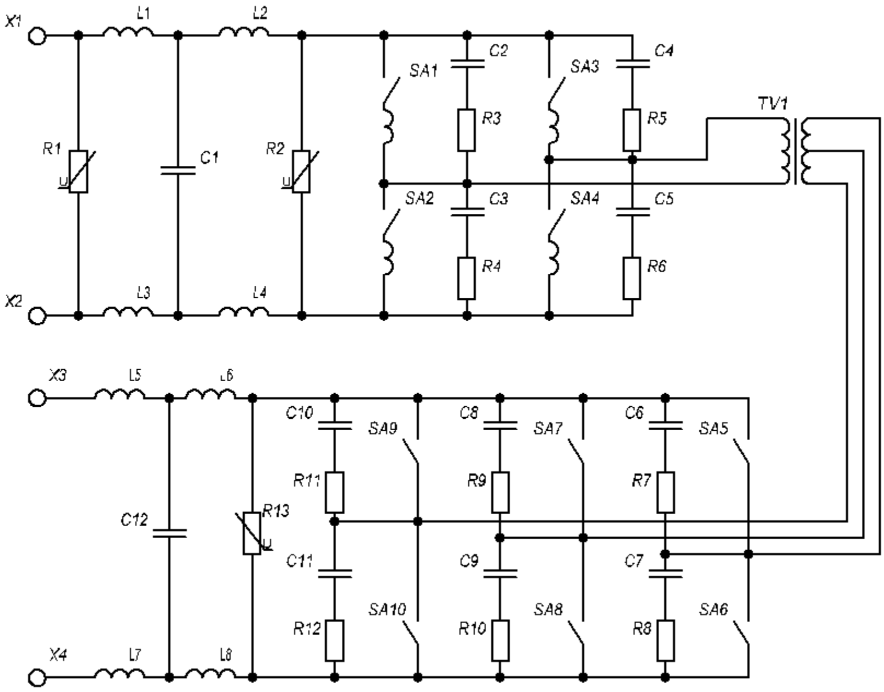

Fig. 3. Electrical scheme of the energy-router, reversible high-frequency transformer.

This allows you to control the energy exchange between the objects of the electrical network while stabilizing the output voltage, which increases the quality and reliability of electricity supply to consumers, helps reduce losses in the transmission of electricity, and reduces the weight and dimensions of such transformers. At the same time, this device performs the functions of a power router (power router), and electrical networks can operate on the principles of "Energy Internet".

When executing the control system of such a device on programmable digital controllers, many additional functions can be combined in it, including protection functions against all possible types of damage and abnormal modes of operation of electrical installations, automatic reclosure (automatic reclosure), automatic separation of the damaged network segment and other automatic Emergency and post-emergency modes, automatic inclusion of a backup power source (ATS), measurement and recording of operational parameters, operational or program control switching devices, fault location on outage on the power line, etc., which gives the right to call such energy routers multifunction devices.

III. Conclusion

For the automation of distribution networks and increasing the reliability of electricity supply, automatic line sectioning devices (reclosers) and automatic switching of the network reserve (sectional switches) are widely used today. Calculations show that the use of reclosers allows several times to reduce the time of interruption of electricity supply and, accordingly, to reduce the damage to consumers from the lack of electricity [4-5]. As follows from the above, the power router can also perform these functions by blocking the operation of the inverter / rectifier of the damaged line. In addition to the large functionality, such a microprocessor control system can also have the functions of a continuous automatic self-test, memorization of events, remote monitoring and prompt modification of settings using an external computer and communication channel or according to a predetermined characteristic. For example, when the line is switched on via the recloser, the setpoint for the protection time can be briefly lowered to accelerate the tripping of a stable short circuit or the entire set of settings is automatically changed when, for example, the primary circuit or the topology of the electrical network is changed.

The use of energy routers as multifunctional devices eliminates the need for the construction of a control panel with a mnemonic network, the room for this shield, the laying of control cables, the cost of mounting a large number of separate measuring and fixing devices, numerous protection and automation relays, etc. The settings of the non-selectively activated digital protection, the direction of power transmission, the parameters of its generation and consumption, can be checked remotely and, if necessary, in the same way changed. Time spent exploring emergency situations, making decisions and eliminating accidents, is measured in several minutes. These advantages of power routers and digital control systems make them the most promising for the creation of modern distribution electric networks, provide additional economic benefit by reducing maintenance costs and reducing the number of damages to electrical installations.

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