Intelligent Transformer: Possibilities and Challenges

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Abstract – This paper covers the concept of an intelligent transformer that is a good candidate to replace a conventional low frequency transformer in the microgrids. As the power production and consumption can vary in a wide range, the new substations have to meet many requirements to guarantee reliable energy management in the autonomous networks. Different topologies of intelligent transformers can be used to meet these requirements. Therefore the advantages and disadvantages of the existing topologies were analyzed. The future trends and challenges are also discussed.

Keywords – Intelligent transformer, high-frequency transformer, microgrid, power electronic converter,

I. INTRODUCTION

Initial years of electric distribution have seen heavy discussions between the DC and AC system proponents. The DC system supported by Thomas Edison was attributed considerable advantages over the AC system e.g. easy integration of energy backup devices, no need for reactive power compensation. On the other hand, the voltage in DC systems was hard to control while AC systems provided an easy way for voltage regulation. The AC system uses the magnetically coupled transformer concept for voltage elevation, transmission over long distances and reduction for residential use. Traditional line-frequency-transformer (LFT) has simple construction, high efficiency and reliability. Moreover, it provides galvanic isolation as well. During the last decade, the basic construction has remained the same, but the improved material technology allowed higher saturation densities and lower hysteresis losses to be achieved, which resulted in very efficient transformers. The efficiency of LFT is considered to be 97 %.

However, LFT is very bulky and heavy. It transforms the voltage directly transferring this way also the unwanted voltage sags, dips and frequency variations to the output. LFT has a very limited voltage and power quality regulation and needs additional flexible AC transmission systems (FACTS) for power quality control. Since the optimal performance of the LFT is designed to be near the full-load, it has high losses in under-load or no-load conditions, also under dc-offset unbalances [1]. In nowadays centralized grid, the LFT meets most of the requirements concerning cost, the efficiency and reliability. However, centralized generating facilities are giving way to smaller, more distributed generation. Thus, it is likely that future power generation and distribution will involve numerous distributed renewable energy sources and micro grids. In order to effectively interconnect power generation and energy storage into a grid or micro grid intelligent energy management (IEM) is needed. IEM substations should have bi-directional energy flow control capability, intelligent control and communication interface. Clearly, traditional low frequency (50 Hz) distribution transformers are not suitable for such demanding applications.

To meet the requirements of the future intelligent network management systems a new concept of a distribution transformer is needed. One possibility is to implement an intelligent transformer (ITR). The ITR was proposed already in the 1980's as an alternative to the LFT for voltage transformation [2]. The ITR, also known as a power electronic transformer or a solid state transformer is a new type of transformer that realizes voltage transformation, galvanic isolation and power quality enhancements in a single device. Its role is to enable active management of distributed energy resources, energy storage devices and different types of loads (domestic or industrial) in the distribution grid. The basic idea behind the ITR is to use a high frequency (f > 1 kHz) transformer instead of a traditional low frequency (50 Hz) distribution transformer. Increasing the frequency allows higher utilization of the magnetic core and reduction in the size of the transformer.

The advantages of this concept were clear, even though the technology for proper demonstration did not exist at that time. The weight and volumes can be up to three times smaller compared to the corresponding LFT due to the use of high frequency. Bi-directional energy flow capability allows connecting storage elements with renewable energy sources and different loads. Moreover, input and output voltages are adjustable with a reactive power compensation feature. Both AC and DC buses are available. The voltage on the DC link, thus on the output, can be easily controlled with a front-end converter e.g. an active rectifier. In addition, the ITR is environmentally friendly since no liquid dielectrics are used for cooling. ITRs can be equipped with advanced communication interface that includes smart metering, diagnostics and distance control features. Eventually, ITRs are also appropriate to be used in single-wire earth return transmission systems [2].

II. BASIC REQUIREMENTS

As a complete DC distribution system will not be available in the near future, the ITR will operate in the already existing AC medium voltage grid. ITRs should be adaptable to different MV and LV levels worldwide. Thus, the ITR will be in the power range of today's power MV/LV distribution LFTs.

TABLE 1

TYPICAL LFT MV/LV DISTRIBUTION TRANSFORMER POWER RATINGS

Apparent power (kVA)	Nominal current (A)	
	237 V	410 V
100	244	141
160	390	225
315	767	444
630	1535	887
1250	3045	1760
1600	3898	2253
2000	4872	2816
2500	7673	4436

TABLE 2

EXISTING MEDIUM VOLTAGE RATINGS

Location	Voltage (kV)				
Europe [1]	3.6	7.2	12	17.5	24
North America [2]	4.75	8.25	15	25.8	
Railway	17.2 [3]	27.5 [4]			

1) 3 phases 50 Hz; 2) 3 phases 60 Hz, 3) 1 phase 16 2/3 Hz, 4) 1 phase 50 or 60 Hz.

TABLE 3

EXISTING LOW VOLTAGE RATINGS

Rated Low voltages (V)				
100/200	120/208	110/220	127/220	120/240
230/400	277/480	347/600	400/690	

2 or 3 phases + neutral, 50 or 60 Hz.

An overview of the most relevant power ratings with nominal current according to the IEC 60076 is given in Table 1. An overview of the most important AC MV- and LV levels in a distribution grid and railway (based on IEC 60038) is given in Table 2 and 3. The standard restricts the use of 3.6 kV and 7.2 kV voltages in public distribution systems. Also, the tolerance of ± 10 % of the nominal voltage in 230/400 and 400/690 systems must be guaranteed.

In addition, ITR must meet the same requirements that are valid for LFT according to the standards. It comprises connection techniques to MV and LV grid, protection against electric shock, sizing and protection of conductors, protection against voltage surges, power factor correction and harmonics filtering, electromagnetic compatibility etc.

III. TOPOLOGIES

Many existing topologies for ITRs as well as for general AC-AC power conversion do not support the bi-directional power flow, which is considered to be a minimum requirement for replacing an LFT. Other important requirements comprise galvanic isolation capability, capability of interconnecting renewable energy sources and energy storage devices.

A good approach to classify ITR topologies and select the appropriate configuration according to the specific needs was introduced in [3] and [4]. According to this classification four basic topology principles can be distinguished:
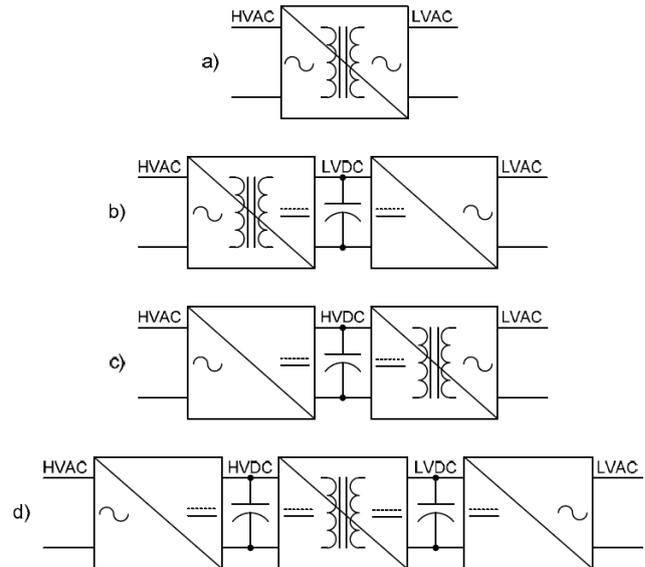

Fig. 1. ITR configurations: a) single-stage AC-AC, b) two-stage with LVDC link, c) two-stage with HVDC link, d) three-stage with HVDC and LVDC links.

a) single-stage topology with direct AC-to-AC conversion,
b) two-stage topology with low voltage DC link (LVDC),
c) two-stage topology with high voltage DC link (HVDC),
d) three-stage topology with both HVDC and LVDC link.

The configuration of these topologies is shown in Fig. 1 [4]. The HVDC link is not suitable for interconnecting the distributed energy storage and distributed renewable energy resource devices since all today's renewable energy resources operate at medium-voltage level. The HV to MV step does not seem to be reasonable due to the need for additional converters that increase the cost and volumes of the whole system. For this reason, topology with the HVDC link is not analyzed further.

A. Single stage topologies

Different single-stage topologies with direct AC-AC conversion exist. Back-to-back VSI is shown in Fig. 2. It is a cascaded connection of a 50 Hz passive transformer and a low-voltage AC-DC-AC converter. It has a bi-directional power flow capability, however it lacks a high frequency transformer and provides no galvanic isolation [5].

Another AC-AC single stage topology with a full bridge converter and a HF transformer was introduced in [4] (see Fig. 3). Here, an input high voltage is turned into a high-frequency square wave and passed through the HF transformer to the low voltage side where it is rectified back to 50 Hz sinusoidal shape voltage. This topology requires simple control, however requires inductive filters on the input and output to allow the buck mode and filter the generated ripple current. Moreover, the lack of the DC link is a major drawback of this topology, thus integration of storage elements and power factor correction would require additional devices which in turn make the system complicated, increase the size and cost of the overall system.
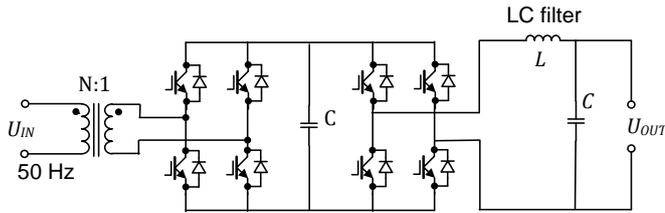
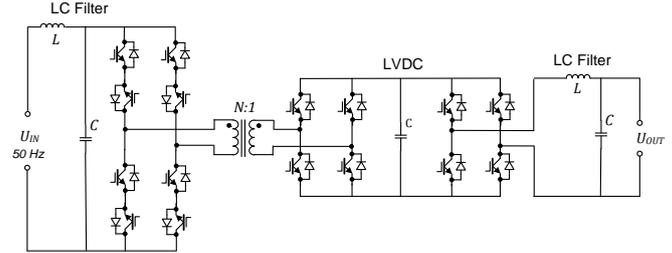Fig. 2. Single-stage topology with LFT and AC-DC-AC converter.

Fig. 4. Two-stage topology with a full bridge converter and a HF transformer.
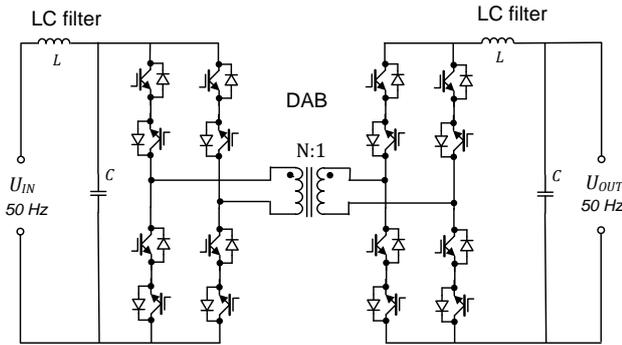

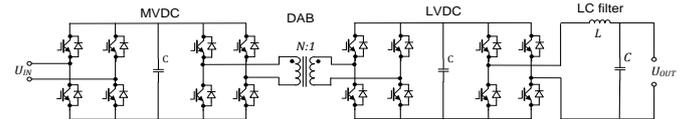Fig. 3. Single stage topology with full bridge converter and HF transformer.

Fig. 5. Three-stage topology system with HVDC/MVDC

B. Two-stage topologies

A two-stage topology based on an AC-DC converter and a PWM inverter is shown in Fig. 4. The switches on the high side must be four-quadrant to withstand bi-polar voltages and currents. A disadvantage of this DC-DC version is the use of two different controls depending on the direction of the power flow.

Use of a dual active bridge (DAB) in the two-stage topology would provide seamless control of the power in both direction and zero voltage switching capability for a wide load range. The disadvantages of this topology are high sensitivity of the average active power flow to leakage inductance variation and the large ripple currents [5]. Also, the reactive power compensation feature is complicated on the HV side.

C. Three stage topologies

Three stage topologies enable several functions that are desirable to ITR [6]-[7]. Three-stage topology comprises rectifying the input AC voltage to a DC voltage, forming this way a MVDC link. Afterwards, the MV is converted into high frequency AC voltage and transferred to the HF transformer, where the voltage level is reduced and rectified again to a low voltage DC level, forming this way a LVDC link. The low DC voltage is converted again into 50 Hz AC voltage. Schematic of this topology is shown in Fig. 5.

The main disadvantage of this topology is the large number of components which results in possibly lower efficiency and reliability. However, the MVDC is suitable for connecting the renewable energy sources to the ITR.

Another three-stage topology with a multilevel-rectifier was proposed in [5]. It uses one flying capacitor multilevel AC-DC converter to provide a HV DC bus for three parallel connected DC-DC DAB converters.

DAB converters provide galvanically isolated power conversion to a LVDC bus. An inverter converts low voltage DC to utility AC voltage. This topology is suitable for connecting to the MV side, because it has input-series-output-parallel configuration that allows blocking of the peak voltage on the MV side. This topology uses compact high frequency transformer, has power flow control, power factor correction and a low voltage DC bus for DG generation, however it has a large number of switches and a complicated configuration.

D. Four wire matrix converter based topologies

Another suitable topology for the ITR was proposed in [8]. This topology is similar to single-stage topologies and is shown in Fig. 6. Input and output links are matrix converters with six bilateral switches, which convert 50 Hz sinusoidal mains voltage to the medium frequency voltage. The inverse function is carried out in the output link in order to convert medium frequency back to 50 Hz sinusoidal voltage. The transformer middle end of the winding is used as the fourth wire to be used as neutral wire. This topology requires a low number of switches, does not require a capacitor on the MV side, has small losses due to fewer switches and bi-directional power flow control capabilities. However, it needs the zero crossing detection of medium frequency voltage for control scheme implementation. Lack of the DC link makes it unsuitable for interconnecting renewable energy sources and energy storage devices into one system.

The topologies were analyzed in detail on the basis of switch count, switch stress, switch losses, control characteristics and the ability to meet the required and desirable functionalities in FREEDM in [4]. Accordingly, all the analyzed topologies require at least three modules. Single-stage topologies are among others with the least elements count and thus least switching losses. However, there is no difference in the switch count between two-stage and three-stage topologies. Low switch losses in single-stage topologies are at the expense of their limited functionalities. The extra DC link in three-stage topologies improves the LVDC link voltage regulation in comparison to two-stage topologies.
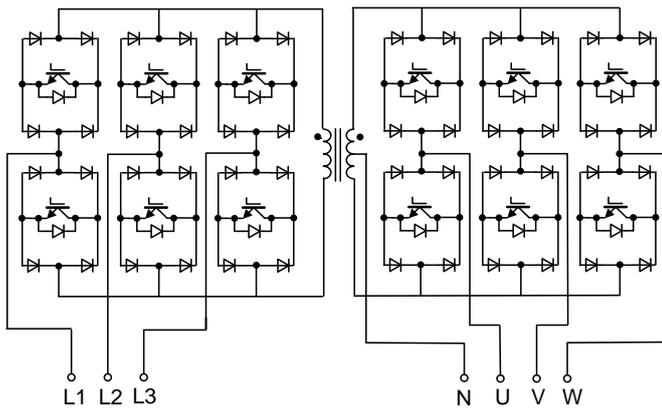
Fig. 6. Direct four-wire matrix converter based ITR topology

Presence of two different voltage level DC links allows interconnecting the energy storage devices and renewable energy sources into one system without additional converters.

According to this comparison three-stage topologies seem to be the most promising due their number of advantages over single- and two-stage topologies. The modular structure based ITR seems to be most advantageous, thus its design and operating principle are described further.

IV. OPERATING PRINCIPLE AND DESIGN OF MODULAR STRUCTURE BASED ITR

A. Base module design

The base module consists of three stages: input, isolation, and output stage [8]-[9]. Input stage is a bi-directional controllable rectifier, which regulates the DC- link voltage and can also be used to shape the input current (reactive power compensation feature). Many topologies are suitable for the input stage most commonly an active front-end bridge rectifier is used. The second stage provides galvanic isolation between the primary and the secondary side and reduces the DC-link voltage.

First, the DC voltage is converted to a high frequency (HF) square-wave signal, then transferred through the HF transformer and finally rectified to form the reduced DC-link voltage on the secondary side. Presence of a two-level DC link allows integrating low-voltage energy storage devices and high voltage (or medium voltage) energy generators into one system. The output stage is a sinewave inverter, which converts reduced DC voltage back to low frequency (50 or 60 Hz) alternating grid voltage. Dual active bridges allow the energy flow to be controlled in both directions and use the soft switching technique.

Soft switching is a feasible solution, facilitated either by adding auxiliary devices such as an auxiliary resonant commutated pole (ARCP) or by using leakage inductance of high-frequency transformers (DAB). However it adds circulated energy, trading conduction loss to the switching loss [5]. ARCP adds a bi-directional switch pole between the neutral point of the DC bus and the midpoint of a main switch leg. Auxiliary switches are turned on during the main switching transient and they provide enough inductive energy

to resonate with snubber capacitors. In a DAB system, the leakage inductance of the high-frequency transformer resonates with snubber capacitors to achieve ZVS [10]. In the case of DAB no extra switching devices are necessary, however soft switching range becomes narrower with the decrease of the load.

B. Phase module design of ITR

IGBTs and high-frequency transformers with distribution voltage ratings are not yet available. Therefore a modular approach can be used to meet these requirements. A modular design consisting of one or several base modules of the ITR is shown in Fig. 7. The ITR allows connecting energy storage devices or controllable DC/DC converter to the LVDC link as shown in Fig. 8. Fig. 9 presents the possibility of using one common inverter with parallel connected phase modules.

C. Three-phase systems

Three-phase voltage systems are used in electrical transmission today, thus all LFTs have three-phase design. Three-phase transformers have three basic winding connections: star, delta and zigzag. As the windings in the LFT, the phase modules of the ITR can be connected correspondingly to different winding connections. The most common winding configuration in distribution networks is Delta/Star connection. An ITR phase module connection is shown in Fig. 10.

Most distribution networks use isolated neutral configuration, since low earth-fault current guarantees reliable work of the grid. However, earth fault can raise voltage in other phases up to factor $\sqrt{3}$ times higher, thus a transformer must be designed to cope with these temporary (until couple of hours) overvoltages.

V. BENEFITS AND CHALLENGES

The ITR must have an efficiency profile that is similar to the LFT. The efficiency of the LFT is normally 97% [2], which is higher than the efficiency of the ITR, however an efficiency rate of 98,1% of the ITR without output inverter has been achieved [11]. The efficiency of the LFT is lowered due to the harmonics caused by residential loads. Major losses in power electronic converter are conduction losses, switching losses and core losses. Conduction losses occur due to the voltage drop on each element in the electric circuit. Switching losses comprise IGBT turn-on/turn-off energy and the diode reverse recovery energy. Transformer core losses are caused due to the hysteresis effect in the core that depend on magnetic flux, switching frequency and on the voltage waveform. Besides main losses, also losses in the gate driver, controller and auxiliary circuits are present. The three major losses were analyzed in [5].

It is also important to notice that besides the advantages of high-frequency on a transformer's size, it can significantly affect the winding resistance by introducing dc resistance, skin and proximity effects [12]. Moreover, the high frequency increases EMI emissions, which may require installing an additional filter and thus reduce the efficiency.
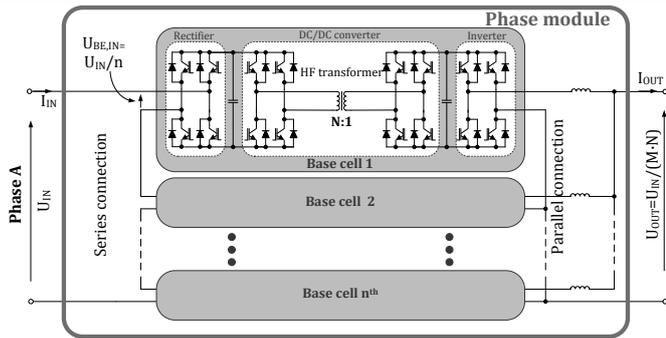
Scientific Journal of Riga Technical University
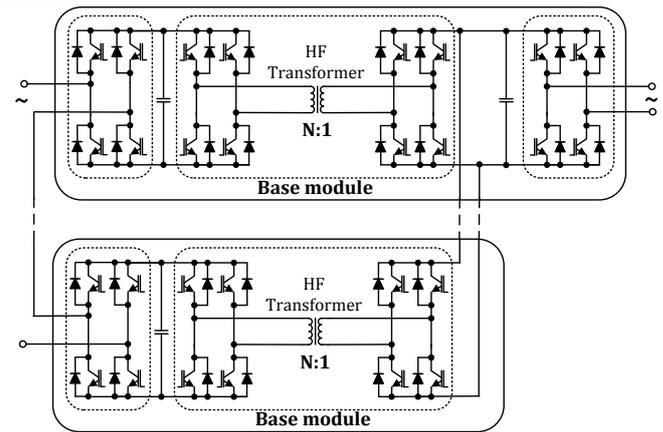Power and Electrical Engineering

DOI: 10.2478/v10144-011-0016-8
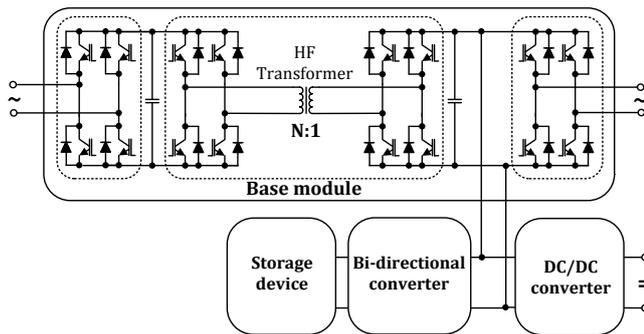
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Volume 29

Fig. 7. One Phase module structure of ITR.

Fig. 8. Connecting an energy storage device and controllable DC source converter to the LVDC link of the ITR.

Fig. 9. A modular three-stage design of the ITR with a common inverter

Fig. 10. Delta/Star connection of three phase modules

Efficiency decreases as the power converters become more complex. Efficiency can be improved by lowering the switching frequency using a multilevel front-end rectifier. Moreover, the topology that uses fewer switches has lower energy circulation and fewer power conversion stages.

Reliability of the ITR is the second highest priority after efficiency. In order to increase the reliability, the following steps can be taken: some redundant cells can be included into the ITR to improve the voltage stress handling in case of failure. It is also likely that the reliability will increase together with the progress of technology [2]. Electrolytic capacitors should be avoided due to their relatively short lifetime (12 000 hours).

The cost of the LFT is much lower than that of comparable ITR, which is mainly caused by the high semiconductor cost. LFTs require additional relay protection, additional elements (e.g. FACTS), stable construction with a built-in oil tank and requires higher amounts of copper. The most expensive elements in ITRs are semiconductors and their sophisticated control circuitry. Using modular design with a common inverter (see Fig. 9) would save the cost. However, it is likely, that with an increase of the manufacture, semiconductor costs will be reduced in the future.

Another issue is the maintenance of the transformer. Maintenance costs of the LFT are relatively low since full maintenance is carried out every 10-15 years while the lifetime of the LFT is usually 30 years under nominal load. Thus, although ITRs do not require oil change, it would require more maintenance of the capacitors, cooling fans, semiconductors.
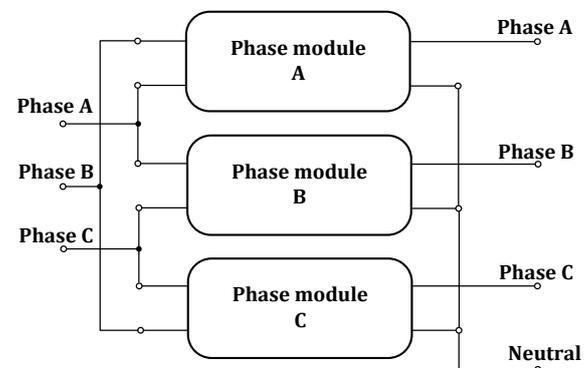
In order to keep the lifetime of semiconductors as high as possible, keeping the operating temperature in the allowed range is essential.

A. ITR in Microgrid

An ITR is a key element of the ITR-based microgrid systems. A microgrid is a possible solution to realize self-powered residential applications for most houses in the country. Reliability of a microgrid is low due to fluctuating renewable energy sources (wind generators, photovoltaic, fuel cells, supercapacitors, diesel generators, electric vehicles or regenerative drives), so an intelligent management is of high importance in such systems. One example of such ITR-based microgrids is a future renewable electric energy delivery and management (FREEDM) system. This is a revolutionary power grid based on power electronics, high bandwidth digital communication and distributed control. It is radically different from today's grids because it replaces electromagnetic devices such as 50 Hz transformers with the ITR [13]. ITRs will play an important role in the protection of a microgrid, which is very sensitive to faults. That is due to meshed network, where finding a fault might be very complicated. Also, the small impedance of microgrid makes conventional phase and distance relays unsuitable for protection. For that reason ITR must have built in protection to identify the fault.

VI. CONCLUSION

This paper covers the new concept of an intelligent transformer, its design, existing topologies, future benefits and challenges. An ITR is a new power electronic based transformer that is intended to operate in microgrids, where renewable energy sources, storage devices and loads are all interconnected into one system. Basic requirements the ITR has to meet are bi-directional energy flow control capability, power factor correction and galvanic isolation. Moreover, the ITR must have an efficiency, reliability and cost comparable to traditional low frequency transformers. In order to operate in the existing network the transformer must be designed to existing power ratings with existing MV and LV levels.

Different single-stage, two-stage, three-stage and also four-wire topologies exist. The most convenient seem to be three-stage topologies with the introduction of a medium-voltage DC link for connecting the power sources and a low-voltage DC link for connecting energy storage devices into one system.

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REFERENCES

[1] Iman-Eini, H.; Farhangi, S.; Schanen, J.-L.; Aime, J.; , "Design of Power Electronic Transformer based on Cascaded H-bridge Multilevel Converter," *Industrial Electronics, 2007. ISIE 2007. IEEE International Symposium on* , vol., no., pp.877-882, 4-7 June 2007.

[2] van der Merwe, J.W.; du T. Mouton, H.; , "The solid-state transformer concept: A new era in power distribution," *AFRICON, 2009. AFRICON '09.* , vol., no., pp.1-6, 23-25 Sept. 2009.

[3] Heinemann, L.; Mauthe, G.; , "The universal power electronics based distribution transformer, an unified approach," *Power Electronics Specialists Conference, 2001. PESC. 2001 IEEE 32nd Annual* , vol.2, no., pp.504-509 vol.2, 2001.

[4] Falcones, S.; Xiaolin Mao; Ayyanar, R.; , "Topology comparison for Solid State Transformer implementation," *Power and Energy Society General Meeting, 2010 IEEE* , vol., no., pp.1-8, 25-29 July 2010.

[5] Hengsi Qin; Kimball, J.W.; , "A comparative efficiency study of silicon-based solid state transformers," *Energy Conversion Congress and Exposition (ECCE), 2010 IEEE* , vol., no., pp.1458-1463, 12-16 Sept. 2010.

[6] Bhattacharya, S.; Tiefu Zhao; Gangyao Wang; Dutta, S.; Seunghun Baek; Yu Du; Parkhideh, B.; Xiaohu Zhou; Huang, A.Q.; , "Design and development of Generation-I silicon based Solid State Transformer," *Applied Power Electronics Conference and Exposition (APEC), 2010 Twenty-Fifth Annual IEEE* , vol., no., pp.1666-1673, 21-25 Feb. 2010.

[7] Banaei, M.R.; Salary, E.; , "Power quality improvement based on novel power electronic transformer," *Power Electronics, Drive Systems and Technologies Conference (PEDSTC), 2011 2nd* , vol., no., pp.286-291, 16-17 Feb. 2011

[8] Mirmousa, H.; Zolghadri, M.R.; , "A Novel Circuit Topology for Three-Phase Four-Wire Distribution Electronic Power Transformer," *Power Electronics and Drive Systems, 2007. PEDS '07. 7th International Conference on* , vol., no., pp.1215-1222, 27-30 Nov. 2007.

[9] Ronan, E.R.; Sudhoff, S.D.; Glover, S.F.; Galloway, D.L.; , "A power electronic-based distribution transformer," *Power Delivery, IEEE Transactions on* , vol.17, no.2, pp.537-543, Apr 2002.

[10] Smith, K.M., Jr.; Smedley, K.M.; , "A comparison of voltage-mode soft-switching methods for PWM converters," *Power Electronics, IEEE Transactions on* , vol.12, no.2, pp.376-386, Mar 1997.

[11] Heinemann, L.; , "Analysis and design of a modular, high power converter with high efficiency for electrical power distribution systems," *Power Electronics Specialists Conference, 2002. pesc 02. 2002 IEEE 33rd Annual* , vol.2, no., pp. 713- 718 vol.2, 2002.

[12] Du, S.B.Y.; Gangyao Wang; Bhattacharya, S.; , "Design considerations of high voltage and high frequency transformer for solid state transformer application," *IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society* , vol., no., pp.421-426, 7-10 Nov. 2010.

[13] Xu She; Lukic, S.; Huang, A.Q.; Bhattacharya, S.; Baran, M.; , "Performance evaluation of solid state transformer based microgrid in FREEDM systems," *Applied Power Electronics Conference and Exposition (APEC), 2011 Twenty-Sixth Annual IEEE* , vol., no., pp.182-188, 6-11 March 2011.

[14] Xiaohu Zhou; Yu Liu; Bhattacharya, S.; Huang, A.; , "New inductor current feedback control with active harmonics injection for inverter stage of solid state transformer," *IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society* , vol., no., pp.593-598, 7-10 Nov. 2010.

[15] Escobar, G.; Mattavelli, P.; Stankovic, A.M.; Valdez, A.A.; Leyva-Ramos, J.; , "An Adaptive Control for UPS to Compensate Unbalance and Harmonic Distortion Using a Combined Capacitor/Load Current Sensing," *Industrial Electronics, IEEE Transactions on* , vol.54, no.2, pp.839-847, April 2007.

[16] Mattavelli, P.;"An improved deadbeat control for UPS using disturbance observers," *Industrial Electronics, IEEE Transactions on* , vol.52, no.1, pp. 206- 212, Feb. 2005

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