A Power Electronics based Transformer design and its Optimization to reduce the losses

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Abstract—A new type of transformer based on Power Electronics (PET), which realizes voltage transformation, galvanic isolation, and power quality improvements in a single device. The PET provides a fundamentally different and more complete approach in transformer design by using power electronics on the primary and secondary sides of the transformer. Several features such as instantaneous voltage regulation, voltage sag compensation and power factor correction can be combined into PET. In the design process, the AC/DC, DC/AC, AC/AC converters and high frequency transformer have been used. One matrix converter operates as AC/AC converter in power electronic transformer. The designed power electronic transformer performs typical functions and has advantages such as power factor correction, voltage sag and swell elimination, voltage flicker reduction and protection capability in fault situations. The proposed power electronic transformer has been modeled using MATLAB/SIMULINK and Power quality improvement with proposed model will be verified by the simulation results.

Index Terms—PET, AC/DC-DC/DC converter

I. INTRODUCTION
Transformer is mostly used in electric and electronic power systems to perform the primary works, as voltage transformation and isolation. A new type transformers works on Power Electronics referred as PET has been introduced, which realizes voltage transformation and galvanic isolation and power quality improvements in a single kit. The PET provides a fundamentally different and more complete approach in transformer design by using power electronics on the primary and secondary sides of the transformer. Several Features such as instantaneous voltage regulation, voltage sag compensation and power factor correction can be combined into PET. Different ways have been presented for realizing the PET, in recent times. In the AC to AC buck converter has been proposed to transform the voltage level directly to different levels and without any isolation transformer.

This approach can perform wearies power quality functions and provide galvanic isolation but they need whether too many power electronic converter devices and DC-link electrolytic capacitors. So, they goes in a rather cumbersome solution. Custom power devices are introduced in the distribution system to deal with various power quality problems faced by industrial and commercial customers due to increase insensitive loads such as computer and adjustable speed drives and use of programmable logic control in the industrial working. Here we investigate the PET that includes three parts: input stage, an isolation stage, and an output stage. Based on power electronics additional features like fast voltage regulation (flicker compensation), reactive power compensation, active neutral-point control, protection of the HV system from harmonic distortion of nonlinear loads and unbalance and protection of the MV system from voltage sags of the HV system (ride-through capability) etc. could be incorporated into an electronic power transformer.

![Basic DC-link PET](image_url)

Fig1.1.Basic DC-link PET
To receive these additional features no change of the distribution system is required and magnetic isolation between the primary and secondary is kept (Fig.1). In this paper a modular design of an electronic power transformer is introduced where dimension and weight of the transformer are decreased.
II. DESIGN AND BACK GROUND

a) Conventional Pets
Distribution transformers are basic equipments in power and distribution systems. They are comparatively inexpensive, highly reliable, and fairly efficient. These disadvantages are becoming increasingly important as power quality becomes more of a concern. In this condition, power electronic based transformer is a best option for protecting from the above problems. This approach for realization of a PET is to use in high frequency modulated Ac to Ac transformer. This design has the advantage of decreasing the transformer size and weight and the stress factor is more reasonable, but it did not provides any benefit in terms of control or power-factor improvement.

Electronic transformer using High Frequency AC link The basic block diagram of the PET using HF (MF) AC-link without DC-link capacitor shown in fig. In this system, the line side AC waveform is modulated with a converter to a high-frequency square-wave and passed through a HF (MF) transformer and again with a converter, it is demodulated to AC form power-frequency. Since the transformer size is inversely proportional to the frequency, the HF (MF) transformer will be much smaller than the power-frequency transformer. So, the transformer size, weight and stress factors reduced considerably.

Fig.3.1. Electronic transformer using High Frequency AC link
An isolated high-frequency link AC to AC converter is said an electronic transformer. The electronic transformer has size and cost advantages to a normal transformer because of high-frequency operation of the magnetic core. From the various methods of electronic transformer, the high-frequency AC link electronic transformer has high-frequency AC power transformation without a DC link. The circuit uses the standardized H-bridge, both side of the high-frequency transformer. A good PWM scheme is proposed, which symmetrically decreases and increases the phase of the left and right legs of the front side converter with respect to the converter used at side. Power Electronic based Transformer.

The above converter does not provide any benefits in terms of protect the critical loads from the instantaneous power interruptions due to lack of energy storage system.

Fig 3.2. Shows the basic block diagram
First stage is an AC/DC converter which is utilized to shape the input current, to correct the input power factor, and to regulate the voltage of primary DC bus. Second stage is an isolation stage which provides the galvanic isolation between the primary and secondary side. In the isolation stage, the DC voltage is converted to a high-frequency square wave voltage, coupled to the secondary of the HF (MF) transformer and is rectified to form the DC link voltage. The output stage is a voltage source inverter which produces the desired AC waveforms. In comparison to first PET, the voltage or current of PET can be flexibly controlled in either side of HF (MF) transformer. It is possible to add energy storage to enhance the ride-through capability of the PET or to prepare integrated interface for distributed resources due to the available DC links. It prevents the voltage or current harmonics to propagate in either side of the...
transformer, even if the input voltage has low order harmonic content or the load.

b) Proposed Pet
The block diagram of the proposed PET is shown in Fig. As can be seen from the Fig3, this is a three-stage design that includes an input stage, an isolation stage and an output stage. Convert the primary low frequency voltage into the DC voltage. The main functions associated with the rectifier control are shaping the input current, controlling the input power factor, and keeping the DC-link voltage at the desired reference value. Many control methods are presented for control of input stage in conventional PET. Fig. 4 shows three phase rectifier with input inductances. A three phase PWM rectifier is used in here, which operates same as input stage of conventional PET.

As can be seen from Fig4, the reference for the active current is derived from the DC voltage outer loop. The reference for the reactive current is set to zero to get unity power factor. The current error signals are input the current regulators and then form the modulation signals. If the d axis of the reference frame is aligned to the grid voltage, we obtain Vin =0.

c) Output Stage
A matrix converter with novel function for square to sinusoidal voltage converter. Matrix converter topology employs six bidirectional switches to convert high frequency single-phase input directly to a power frequency (50/60 Hz) three-phase output

The proposed converter generates desired output voltage with suitable shape and frequency. Several modulation strategies have been proposed for traditional inverters. Among these methods, space vector pulse width modulation (SVM) became a standard for the switching power converters. Space Vector Pulse Width Modulation identifies each switching state of a two- or multilevel converter as a point in complex space. Then a reference pharos rotating in the plane at the fundamental frequency is sampled within each switching period, and the nearest three converter switched states are selected with duty cycles calculated to achieve the same volt-second average as the sampled reference phase.

This directly controls the converter line-to-line voltages, and only implicitly develops the phase leg voltages an analytical expression is derived for the optimal apportioning factor that results in minimum THD. Comparing with pulse width modulation space vector modulation has more switching patterns. In proposed PET, space vector modulation technique applied to a matrix converter is employed. The main point of switching is, with changing of polarity in input sources on switches are turned off and other switches in arms are turned on. Fig7.

d) Frequency Converter Topologies
Fig. 1 shows the basic design of an electronic power transformer coupling a HV grid with a MV grid. A frequency converter on each side of the transformer connected directly to the HV resp. MV grid transforms voltages and currents from basic
frequency of 50Hz into a HV Frequency MF MV Frequency Convener Transformer Convener

![Basic power electronic transformer circuit](image)

**Fig 3.8. Basic power electronic transformer circuit**

Electronic Power Transformer medium frequency (MF) fMp. Different frequency converter schemes are presented and discussed relating to a realization with modem power electronic devices.

e) Proposed Design

Due to the different medium-voltage levels and the installation of the whole electronic power transformer in few portable containers a modular assembly is suggested. In [16] a classification system for multilevel, multi-cellular power converters with the following nomenclature is introduced XMLNY, with

- X, number of DC links on Side A
- Y, number of DC links on Side B
- L, Number of MF transformers
- M, windings per MF transformer (side A)
- N, windings per MF transformer (side B).

At this point electronic power transformer building blocks shown in Fig. 5 with a structure are proposed and the basic modules are considered separately.

i. Medium-Voltage Module

The medium-voltage module consists of a H-bridge VSC, with a rated dc voltage of 9.6kV. For this, a series connection of HV-IGBTs per valve, moreover the converters connected to the HV system may be designed as multilevel converters by additional clamping diodes or flying capacitors. This means an increasing complexity of each converter and its control, but provides the possibility to reduce switching losses by switching with fundamental frequency without insufficient harmonic distortion in the HV system. The optimal number of voltage levels has to be estimated based on switching frequency and losses harmonic distortion, ac filter size and complexity of the additional voltage level control for each H-bridge multilevel converter. At the HV side a maximum output voltage rms value of 35.2kV is achieved by the series connection of the three H-bridge VSCs.

![Series isolated AC-DC converters](image)

**Fig 3.12. Series isolated AC-DC converters**

iii. Dc-Dc Module

The dc-dc module consists of three H-bridge VSCs, each working with the rated dc-link voltage of 16.6kV, a Yd5 medium-frequency transformer and a three-phase VSC, back-to-back connected to the medium-voltage module with the rated dc-link voltage of 9.6kV. All VSCs are working with fundamental switching frequency, providing a medium frequency three-phase six-step resp. square-wave voltage at the terminals of the transformer.

![Converter configuration](image)
In order to reduce magnetization and eddy-current losses a special core material is used like ferrite or amorphous alloy, but cost and specific mass are also significant. In [IS] the design of a 1 MW cable-wound high-voltage single-phase transformer is presented.

iv. Electronic Power Transformer Designs

Fig. 7 shows the design of electronic power transformers for the two most common HVMV conversions in German distribution grids. For simplicity only one of three phases is shown. Two HV modules are connected in series on the HV side to achieve a line-to-neutral rms voltages of about 70.4kV, taking 10% overvoltage for the l10kV grid into account.

For a 20kV medium voltage grid (Fig. 7 (a)) a series connection of two MV modules is needed. The 17% voltage reserve is taken into consideration for dynamic voltage regulation. Attention has to be paid to voltage balancing of the two MV dc buses by the control of the MV modules.

For a l0kV medium-voltage grid (Fig. 7 (b)) only one MV module is needed, therefore only half of the power in comparison to the 110kV/20kV conversion can be transformed. The two Dc-Dc modules are connected in parallel on the MV side, feeding the same MV dc bus. Other voltage levels can be reached by series connection of other modules and/or by A-resp. Y-connection of the single-phase modules.

In comparison, the single-phase power electronic-based distribution transformer presented in [19, 20] consists of a unity power factor active rectifier for each input stage module (resp. HV module) and a hard-switched phase-shifted bridge for each isolation stage module and provides only single-directional power flow.

III. SIMULATION

To evaluate the expected performance of the PET, the design was simulated to predict steady state performance. A prototype based on the proposed topology is simulated using MATLAB/SIMULINK. Operation of proposed PET is described by Fig. 10. Fig. 10(a) shows input line voltage of PET. As it can be seen in Fig. 10(b), the DC-link voltage of input stage is 6800 V. Fig. 10(c) depicts the output voltage of VSC in isolation stage that transforms DC voltage to medium frequency AC voltage as the transformer primary voltage. In the output stage, the medium frequency voltage is revealed as a 50 Hz waveform by AC/AC matrix converter, and synchronous machine in connected after the filter rotor current, speed and torque of the Permanent Magnet Synchronous machine.

To evaluate the expected performance of this Solid State Transformer (SST), the design was simulated to predict steady-state and transient behavior. The simulation language chosen was ACSL, which is a general-purpose state variable based simulator. All switches and diodes as well as all passive devices were included in the simulation model, resulting in a 122°d order system.

Descriptions and values of the principal parameters are set forth and illustrate several of the important waveforms recorded from a steady-state simulation at nominal voltage rated output load and a lagging load power factor of 0.8. From the figure it is clear that the input voltage (a) and current (b) are in phase and the current is sinusoidal.

Input Controlling Circuit of Converter

As can be seen from diagrams the reference for the active current is derived from the DC voltage outer loop. The reference for the reactive current is set to zero to get unity power factor. The current error signals are input the current regulators and then form the modulation signals. If the d axis of the reference frame is aligned to the grid voltage, we obtain Vinq =0. Each input-stage module consists of a unity power factor active rectifier, with the rectified ac fed
to a boost converter. This configuration is shown in Fig. 2. By control of the active switch in the boost converter, current entering the rectifier can be shaped into a sinusoid while the input voltage is regulated. An overview of the control system for the input stage is illustrated in Fig. 3. In the Voltage Regulator, the output dc voltage is compared with the required level and the result is used to formulate the input current magnitude command current. This is passed to the Current Command Synthesizer, where it is combined with the results of the Voltage Observer.

An overview of the control system for the input stage is illustrated in Fig. 3. In the Voltage Regulator, the output dc voltage is compared with the required level and the result is used to formulate the input current magnitude command current. This is passed to the Current Command Synthesizer, where it is combined with the results of the Voltage Observer.

In the isolation stage as shown in the above diagram, we have 4 H-Bridge cells and each have their own functions. As we can see the 4 pulses were given to all H-Bridge cells and their function were explained. As sinusoidal wave from is compared with the carrier waveforms applied to the circuit.

### IV. SIMULATION RESULT

In regard to the efficiency of the design, simulation studies have shown that the input stage efficiency should be very high (about 99%) and relatively "flat" with power level. The output stage is the least efficient; just over 96% at full load. Therefore, the combined efficiency of the SST described herein should be able to exceed 90%. To achieve greater efficiencies in a solid-state transformer, soft switching could be employed to reduce switching losses in the isolation and output stages. The use of (new) high-voltage silicon carbide (Sic) Schottkey diodes would also significantly reduce switching and conduction losses.
Voltage Swell

In this paper a new configuration of power electronic transformer with DC-Link capacitor has been proposed. To obtain higher efficiency, the AC/DC and DC/AC converters have been integrated in one converter. The topology described in this paper has many advantages such as power factor correction, voltage regulation, voltage sag and swell elimination, voltage flicker reduction. In proposed PET one AC/AC matrix converter is used to replace two converters and switching of matrix converter is easy and not complex. Simulation results showed some of advantages in proposed PET.

Different frequency-converter topologies for an electronic transformer are presented and discussed relating to a realization with modem power electronic devices. Due to the different medium voltage levels in distribution grids and the installation of the whole electronic power transformer in few portable containers, a modular assembly is chosen. For this, the design of electronic power transformer building blocks are presented, using the power electronics, additional features incorporated in an electronic power transformer like fist voltage regulation, reactive power compensation, and ride-through capability etc. are described. Further investigations into the design of the building blocks together with steady-state and dynamic simulations will be done, to give further details on power, voltage and current ratings, on weight and dimensions and on cost.

REFERENCES


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