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Insertion of High Frequency Solid State Transformer to Electric Power System And Analysis of its performance

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ABSTRACT

The spread of distributed power stations, especially small power stations that use renewable energy sources, as well as the connection of a large number of distributed power stations to the network led to the necessity of making some changes in the electrical distribution system. Therefore, the Solid State Transformer (SST) has recently emerged as a suitable alternative to the traditional transformer. SST is characterized by its small size and weight, and as the possibility of controlling the direction and amount of power flow, improving the quality of power, the possibility of controlling voltage, compensating reactive power and other advantages that are not available in the traditional transformer that can be of paramount importance to the development of the power system. This paper reviews solid state transformers in terms of their components, working method, mathematical analysis, design steps, and control process. ANSYS Maxwell 3D software was used to design and model the high frequency isolation transformer and a working model of the core-type high frequency isolation transformer was presented. It was found through the results of the study and analysis of the solid-state transformer that it would be a suitable alternative to the traditional transformer that works at high frequencies.

Keywords:

Distributed power stations; renewable energy sources; Solid State Transformer; ANSYS Maxwell

1. INTRODUCTION

The smart grid has received widespread research interest lately, due to the mitigation of the harmful environmental impacts resulting from reliance on traditional fossil fuels and the modern endeavor to reduce the amount of greenhouse gas emissions by relying on alternative renewable energies. Renewable energy sources include wind energy, photovoltaic energy and other energies. However, the high use of renewable energy sources will bring some challenges to the current electric power system, which requires making some changes to the current electric power distribution system, in order to introduce more renewable energy sources into the electric power system [1]. Some of these changes are the introduction of new equipment into the electrical power system or the replacement of some equipment with equipment that can meet the requirements of the new situation. One of these changes is to replace the traditional transformer with a solid-state transformer, which will lead to providing additional advantages to the electrical power system, such as the possibility of controlling the direction of power, compensation for VAR, voltage regulation, improving power factor and improving the quality of electrical power, as well as the intrinsic advantages of the transformer such as small size and light weight that the solid-state transformer enjoys. In general, a solid-state transformer consists of power electronics converters, a high-frequency transformer, and control circuits as well as auxiliary circuits. The high-frequency transformer performs the step-up and step-down function as well as the isolation function, while the power electronics converters provide additional advantages of the solid-state transformer [2] [3].

Several research papers and studies have been presented on solid-state transformers and high-frequency transformer design method. In 2009, van der Merwe [4] and others studied the concept of a solid-state transformer as a viable alternative to a conventional transformer in distribution circuits, highlighting the benefits of a solid-state transformer in terms of improvements in areas where the problems faced by distribution networks occur, as well as providing other benefits to the solid state transformer, He also identified some obstacles to the solid state converter, and analyzed and discussed the effects of these obstacles. And Liang Wang [5] et al. in 2015 presented a power and voltage balance control and he used cascaded H-bridge multilevel with solid-state transformers. The DC-DC stage researchers used the active dual bridge and the researchers presented simulation results to validate the performance of the controller and apply it to a small network. Briz [6] et al. presented in 2016 a paper focusing on two design concepts for power electronics converter used with a solid-state transformer; one is the cascading H Bridge and the other is the modular multilevel modulator (MMC). They also presented an analysis in which they explained the number of cells required and indicated the characteristics, functions and potential uses of these converters. In 2017, Gerardo Guerra [7] and others built a solid-state switch model in Open DDS. The objective of this proposal was to develop a solid-state transformer model which can be useful for evaluating the impact that replacing conventional transformers with solid state transformers can have on the performance of a distribution system. Through the simulation results obtained by the researchers, it was found that a positive effect on the voltages should be expected at the levels of medium voltage and low voltage, but the efficiency of solid-state transformer designs must be improved. In the year 2020, M. A. Hannan [8] and others reviewed in detail the topography of the solid-state transformer suitable for different voltage levels and types of solid-state transformer depending on the number of phases that the transformer consists of, methods of control, and their applications in different directions. The researchers also discussed the configuration of the solid-state transformer with its design and characteristics, in addition to explaining the different models for control systems. Then, the researchers highlighted many factors affecting the solid-state transformer, including the current problems and challenges, and made recommendations to improve the formation and development of the solid-state transformer.

2. The concept of solid state transformers

Solid-state inverters are an emerging technology that can influence the development of many areas such as smart grids, electric power systems that use renewable energy sources and traction systems[9]. SST technology converts the input low-frequency electrical power into high-frequency electrical power through the power electronics circuits and returns it to low-frequency power at both ends of the output.

The electric power system mainly consists of generating stations, transmission lines and loads as shown in Figure 1. To transfer electrical power with little losses, we need to raise the voltage to a certain level and then lower it to other standard levels, and power transformers and distribution transformers perform this function. Conventional transformers are limited to managing (increasing or decreasing) voltage levels only, but are not able to handle power quality situations, such as entering harmonics, voltage fluctuation, etc. For this reason, solid-state transformers have been turned towards it, as it can deal with power quality situations and add additional advantages to electrical power system transformers, not only reducing and raising the voltage, as well as their low weight compared to the traditional transformer.

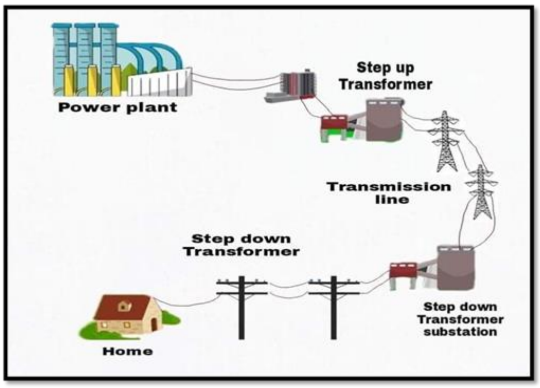

Fig. 1 Components of an electrical power system

3. Classification of solid state transformers

The structure of solid-state transformers is classified based on the number of phases of power conversion and the electrical features that make up them into four classes. All types of solid-state transformers have an isolated AC-AC switching function, whether this function is performed directly in one phase or indirectly in more than one phase, regardless of their differences in the topography of the transformer design. Figure 2 shows the types of solid state transformers based on the number of phases they are composed of.Tables and Figures must becenter-presented as shown below and cited in the manuscript according to their appearance sequence [8][10][13].

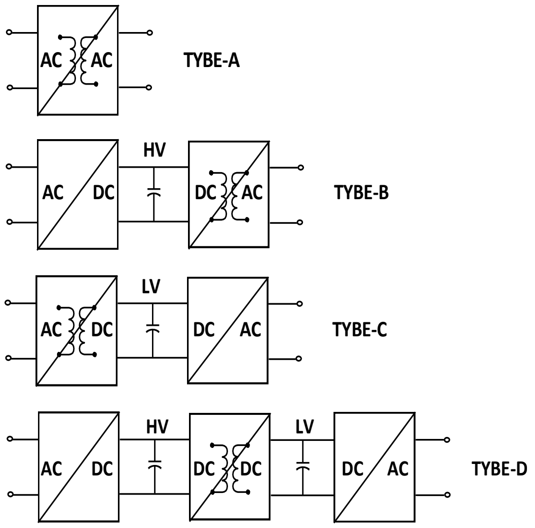

Fig. 2 Topography classification of solid state transformers.

The first type is the conversion of power from high-voltage alternating current (HVAC) to low-voltage alternating current (LVAC) through a high-frequency transformer [8]. This type is the simplest topography for solid-state transformers that contain only direct power conversion with isolation by a high-frequency transformer for high-to-low-voltage reduction [10]. This type works with better efficiency and reliability than the topography of three-phase solid-state transformers because the conduction losses and switching losses of the switches are small. This type has a high switching frequency and does not require many capacitors. Single phase topography uses the phase difference angle between the primary and secondary bridges to control the direction and amount of energy transmitted. The phase difference angle controls the amount of power transferred to the load. Single-phase solid-state transformers do not have a DC connection, which severely limits their use, for example, they cannot be used with renewable energy sources and energy storage devices. The absence of the DC connection causes a loss of the ability to regulate voltage and compensate for the reactive power; Hence there is no correction for the input power factor. Therefore, single-stage topography has limited applications [11].

The main difference between single-stage and two-stage for solid-state transformers is the additional design of the DC link as in this type. DC link is formed in the high or low voltage side. The energy flow is bidirectional; However, it can be modified to a unidirectional by deploying an uncontrolled rectifier at the low voltage side of the high frequency transformer. This topography requires a complex transformation method as well as a large number of switches [12].

While three-stage solid-state transformers are the most common topography and have isolation by high-frequency transformer in DC-DC stage, they provide more characteristics for the transformer. Aside from the low size and weight of solid state inverters, they are also capable of improving performance in distribution and transmission networks. The three-stage DC two-link solid-state transformer topography is designed capable of addressing power quality problems and also providing and using any devices in the MV or LV of the two DC connections [13]. Three-stage topography is superior to single-stage and two-stage topography in terms of voltage regulation, protection, power factor regulation and use in energy storage applications, renewable energy sources, and distributed power applications. Three-stage solid-state transformers are also designed and used with smart grid applications in which the power flow is bidirectional to transfer energy from low voltage to high voltage or vice versa[14].

4. Three-stage Solid State Transformers

The structure of three-stage solid-state transformers is represented by a rectifier (AC / DC) in the first stage, a (DC-DC) converter in the second stage, and an inverter (DC / AC) in the third stage. The following is an explanation and a statement for these stages.

4.1. First stage (AC/DC)

In the input stage of the SST, multi-level power electronics converters are used since the solid-state transformer are connected to a medium voltage network. Several types of power electronics converters are used for this stage, like a two- or three-level conventional voltage source modulator, a cascade H-bridge modulator (CHB), and a modular multi-level modulator (MMC) [15].

4.2. Second stage (DC/DC)

The second stage is the DC-DC conversion stage and is the core of the SST. This stage consists of three parts: a (DC→AC) inverter, a high frequency transformer and an (AC→DC) converter. Several structures, which are different in complexity, operating characteristics and performance, can be used at this stage. Of these structures most suitable for SST technology are the single active bridge, the dual active bridge, the two-way isolated current-multiplier modulator and the LLC resonant modulator. In this paper, the single active bridge and the double active bridge will be discussed, as the single active bridge (SAB) consists of two bridges with a high-frequency transformer in the middle as shown in Figure 3 The dual active bridge (DAB) also consists of two bridges with a high-frequency transformer in the middle as shown in Figure 4, but it differs from the single active bridge in that both bridges are controlled, unlike the single active bridge, the first bridge is controlled As for the second bridge, it will be passive.

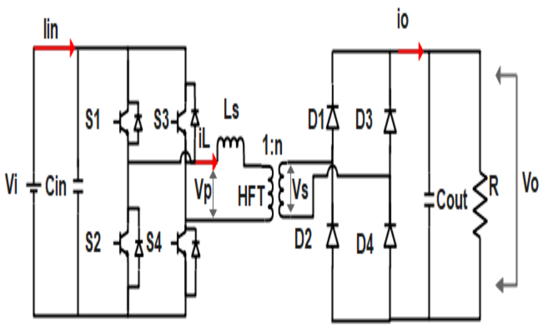

Fig. 3 Single Active Bridge

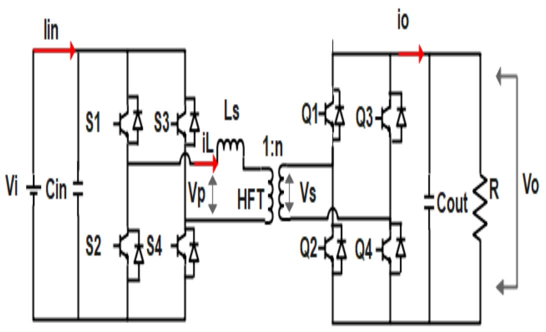

Fig. 4 Dual Active Bridge

Figure 5 shows the switch operation pulses, input voltage, output voltage, inductance current and output current of a SAB converter operating in the Discontinuous Conduction Mode.

α is the phase shift angle, β is the damping angle, and Φ is the zero current

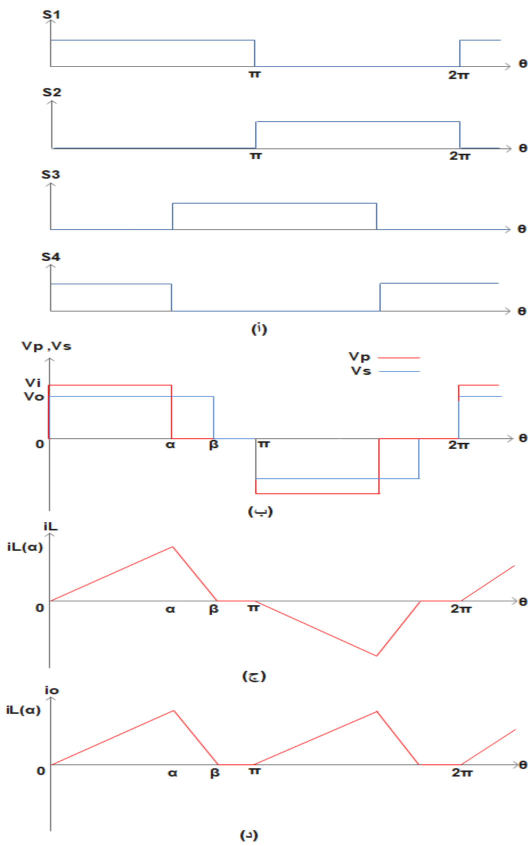

Fig. 5 Switch operation pulses and voltage and current waves of the single active bridge in discontinuous conduction mode

The output current of the single active bridge is calculated from the following equation:

$$i_{L(\alpha)} = i_{L(0)} + \int_0^{\alpha} \frac{V_L}{\omega L} d\theta \; = 0 + \frac{V_i - V_o}{\omega L} \alpha \quad \ldots\ldots\ldots (1)$$

$$i_{L(\beta)} = i_{L(\alpha)} + \int_{\alpha}^{\beta} \frac{V_L}{\omega L} d\theta \; = i_{L(\alpha)} - \frac{V_o}{\omega L}(\beta - \alpha) = 0 \quad \ldots\ldots\ldots (2)$$

$$I_{o(DCM)} = \frac{1}{\pi}\left(\frac{i_{L(\alpha)}.\alpha}{2} + \frac{i_{L(\alpha)}.(\beta - \alpha)}{2}\right) \ldots\ldots\ldots (3)$$

$$I_{o(DCM)} = \frac{V_i}{2\omega L}\frac{\alpha^2}{\pi}\left(\frac{V_i}{V_o} - 1\right) \quad \ldots\ldots\ldots (4)$$

While the value of the output power and the output voltage of the single active bridge are calculated from the following equations:

$$P_{o(DCM)} = \frac{V_i V_o}{2\omega L}\frac{\alpha^2}{\pi}\left(\frac{V_i}{V_o} - 1\right) \quad \ldots\ldots\ldots (5)$$

$$V_{o(DCM)} = V_i \frac{R_L}{4\pi}\frac{\alpha^2}{\omega L}\left(-1 + \sqrt{1 + \frac{8\pi\omega L}{R_L \alpha^2}}\right) \ldots\ldots (6)$$

Figure 6 shows the switch operation pulses, input voltage, output voltage, inductance current and output current, of a DAB operating in the forward mode condition.

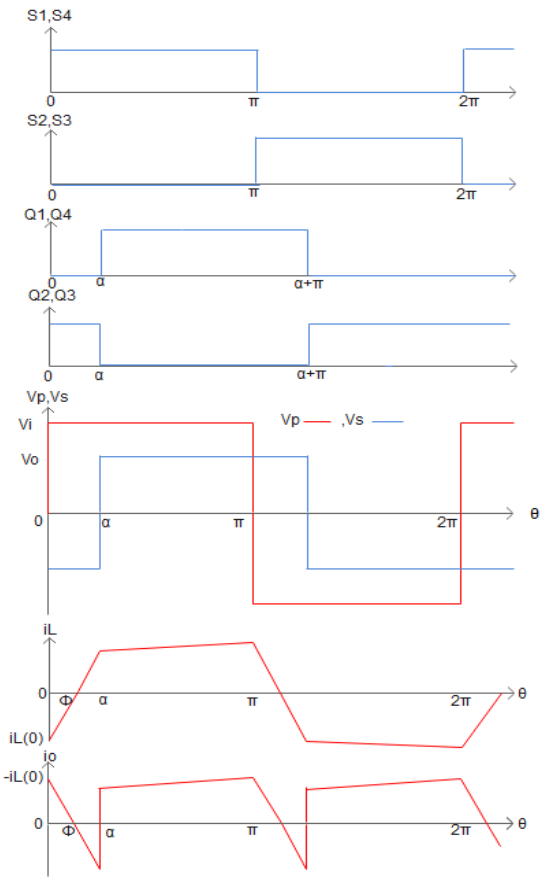

Fig. 6 Switch operation pulses and voltage and current waves of the dual active bridge in forward mode condition

The output current of the dual active bridge is calculated from the following equation:

$$I_o = \frac{V_i}{\omega L}\alpha\left(1-\frac{\alpha}{\pi}\right) \quad \dots\dots\dots (7)$$

And through Equation 4, we can calculate the value of the out power and the output voltage.

$$P_o = \frac{V_i V_o}{\omega L}\alpha\left(1-\frac{\alpha}{\pi}\right) \quad \dots\dots\dots (8)$$

$$V_o = R_L\frac{V_i}{\omega L}\alpha\left(1-\frac{\alpha}{\pi}\right) \quad \dots\dots\dots (9)$$

From Equation 1 we notice that the output current of the single active bridge depends on the value of the output voltage, while we note from Equation 4 that the output current of the dual active bridge does not depend on the value of the output voltage.

4.3. Third stage (DC/AC)

This stage is used to convert LVDC to LVAC. This stage has low input voltage so we do not need multi-level power electronics converters as in the first stage. The main feature of this stage is the output waveform. This stage is able to regulate the voltage waveform to the desired voltage waveform, which is on the load terminals [16]. Moreover, this stage contains many other auxiliary services such as network frequency regulation, online load determination, overload control, and reverse power flow limitation [17]. At this stage, a single-phase inverter consisting of four switches can be used in the case of working on one phase, or a three-phase inverter consisting of six switches can be used.

5. High Frequency Transformers

The High Frequency Transformer is the most important part of the second stage (DC-DC) of a solid-state transformer, and this stage is the core of the SST, which greatly reduces the overall size and weight of the transformer compared to conventional (Low Frequency Transformer). This advantage is achieved due to the fact that the high frequency of the magnetic field requires only a small size of coils [18]. In this compact transformer, the primary and secondary sides are also insulated. Figure 7 shows a high-frequency transformer connected at the primary terminal to the first converter (DAB, SAB, or others), where a high-frequency AC is projected to the primary winding terminals of a high-frequency transformer. Then the magnetic field generated in the primary coils is transmitted to the secondary coils and thus generates the required voltage level at a high frequency. So we note that it has the same concept of conventional transformer; but it works at higher frequencies [8].

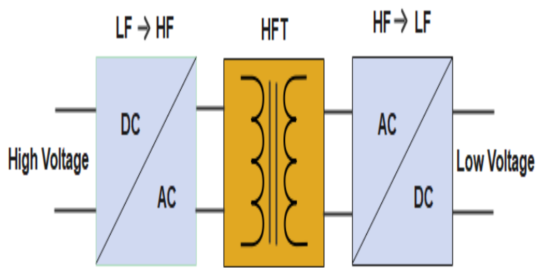

Fig. 7 DC-DC converter with high frequency transformer

Operating at high frequencies leads to increased losses in the transformer core and increased temperature, and therefore the magnetic material used to manufacture the transformer core must be chosen with high saturation flux density and with specific losses to achieve high efficiency and good power density [19]. Since low size and weight is a desirable characteristic of a high frequency transformer, so the insulation requirements and temperature levels must be carefully considered [19]. As for the selection of wires, the effects of crust and proximity in the coils must be taken into account, because with the increase in operating frequency, the effects of crust and proximity in the coils will increase, so special attention must be given to the selection of wires [19]. Also, attention should be paid to the shape of the core, the way coils are placed in the core, and the value of the leakage inductance.

The core-type high-frequency converter is designed to operate at frequency 10KHZ. Ferrite was used to manufacture the core of the transformer because the ferrite material has lower core losses than what it is in other materials used to manufacture the transformer core. Litz wire was used for primary and secondary windings. Litz wire reduces conductor resistance by dividing the conductor into small insulated conductive strands. Each of the very fine strands in the wire are isolated from the other strands around it. These strands form a thicker wire with a thickness equal to the desired wire size. Thin wire strands give better high-frequency characteristics. Table 1 shows the characteristics of the designed transformer.

Table 1: Specifications of the core-type single-phase high-frequency transformer

Parameter	Value
Power	2 kVA
Input Voltage	200 V
Output Voltage	200 V
Frequency	10 kHz
Core Material Type	ferrite
Wire Type	Litz wire
The number of turns of the primary coil	45 turn
The number of turns of the secondary coil	45 turn

The simulation model of the transformer was built using ANSYS Maxwell as shown in Figure 8

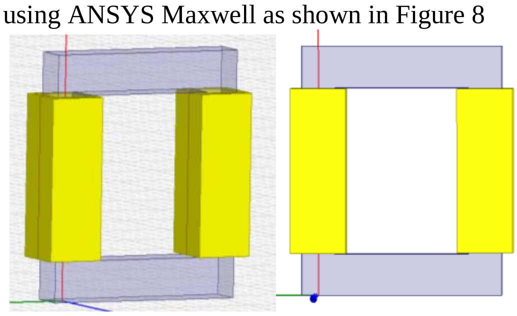

Fig. 8 3D design of a core-type high-frequency transformer

Figure 9 shows the practical model of the designed high-frequency transformer

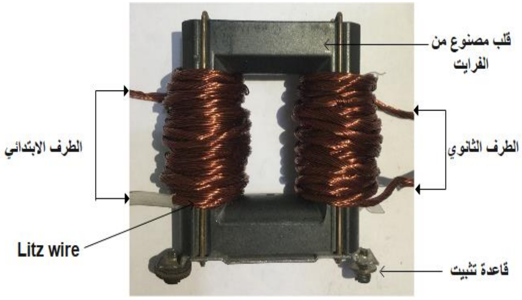

Fig. 9 the practical model of the designed high-frequency transformer

6. Results And Discussions

Figure 10 shows the single active bridge modeled using Matlab/Simulink and the simulation was performed at 10 kHz by connecting the model to an input DC source where DC to AC is converted by square wave, which is the input of a high frequency converter. A model of the phase shift control circuit was built to control this circuit and a PI controller was used to regulate the voltage. After completing the modeling process for the components and components of the single active bridge, the model was run and simulated according to the values shown in Table 2.

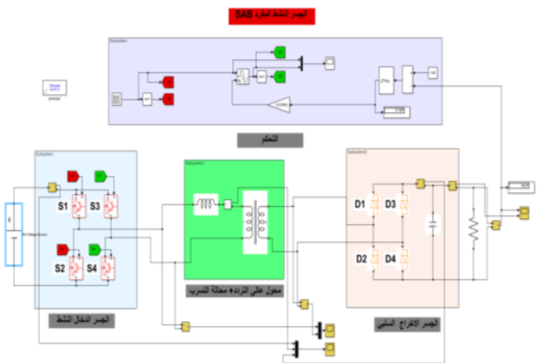

Fig. 10 Power circuit and control circuit of single active bridge

Table 2:Simulated data and values for the circuit SAB .

Parameter	Value
Input Voltage (V_{in})	250 V
Output Voltage (V_o)	100 V
Power for high frequency transformer (P)	2000 KVA
Tran ratio of high frequency transformer(n)	1/2
Frequency (f)	10 KHZ
Leakage inductance	100 µH
Output capacitor (C_o)	900 µF
Resistance (R_o)	10 Ω

Figure 11 shows the primary and secondary voltages of the high-frequency transformer, Figure 12 shows the input current to the circuit and Figure 13 shows the inductance current.

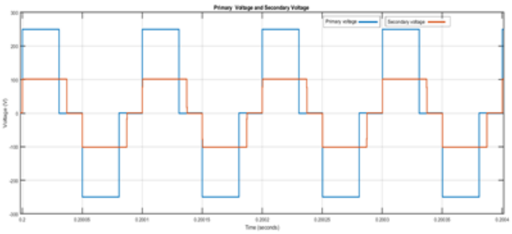

Fig. 11 Primary voltage (Vp) and secondary voltage (Vs) of a high frequency transformer

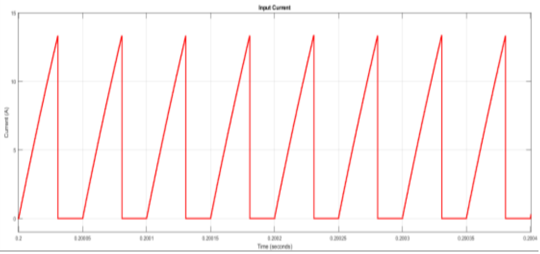

Fig. 12 input current (Iin)

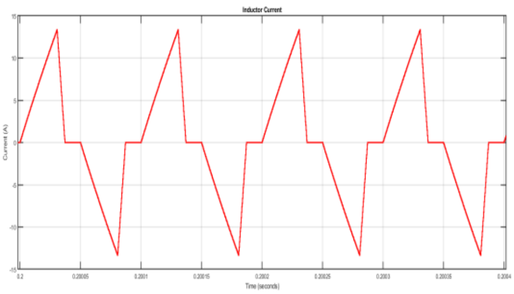

Fig. 13 inductance current (iL)

We notice from Figure 10 and Figure 12 that in the period in which the primary and secondary voltages are zero, the inductance current is also zero, meaning that the circuit operates in the case of intermittent conduction. Figure 14 shows the output voltage and output current. It is clear from the shape of the output voltage and output current of the circuit that the control elements are working correctly as the voltage and current are stabilized at the required value.

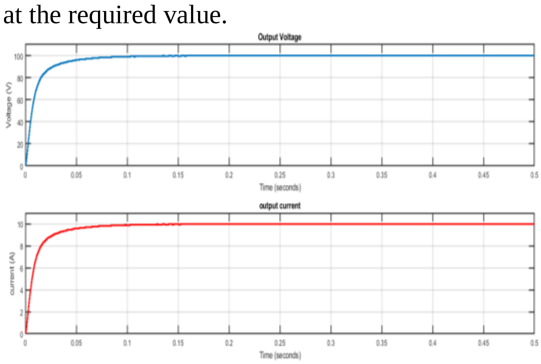

Fig. 14 Output voltage and output current for SAB

7. Conclusion

This paper describes the concept of a solid-state transformer as an isolated transformer that takes advantage of the blend of power electronics transformers and high-frequency transformers. Replacing the traditional transformer that works at low frequencies with a solid state transformer that works at medium frequencies will facilitate the process of transferring and assembling these transformers and allow the power to be transmitted to both ends and provide many functions such as regulating the AVR, improving the power factor, addressing power quality problems and the ability to connect distributed power sources with the network. In this paper, the types of solid-state transformers were discussed, as it was found that the three-phase solid-state transformer has better characteristics than the rest of the types, as it has a direct current connection at the high voltage end and the low voltage end. This feature adds great advantages to the transformer. One of these advantages is the possibility of controlling its voltage the output and the amount of output power by using the single active bridge or the double active bridge. The simulation results of the single active bridge using the MATLAB/Simulink program showed that the output voltage and the output power can be regulated using the control circuits that depend on the phase shift method, as the use of a PI controller controller enables From voltage regulation, the amount of creep angle determines the amount of power output.

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إدخال محول الحالة الصلبة ذات التردد العالى إلى نظام القدرة الكهربائية و تحليل أدائها

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الملخص

أدى انتشار محطات التوليد الموزعة وخاصة المحطات الصغيرة التي تستخدم مصادر الطاقة المتجددة وربط عدد كبير من محطات التوليد الموزعة بالشبكة إلى ضرورة إجراء بعض التغييرات في نظام التوزيع الكهربائي. لذلك ، ظهر محول الحالة الصلبة (SST) مؤخرًا كبديل مناسب للمحول التقليدي. يتميز SST بصغر حجمه ووزنه ، وإمكانية التحكم في اتجاه وكمية تدفق الطاقة ، وتحسين جودة الطاقة ، وإمكانية التحكم في الجهد ، وتعويض القدرة التفاعلية وغيرها من المزايا التي لا تتوفر في المحولات التقليدية التي يمكن أن تكون ذات أهمية قصوى لتطوير نظام الطاقة. تستعرض هذه الورقة محولات الحالة الصلبة من حيث مكوناتها ، وطريقة عملها ، والتحليل الرياضي ، وخطوات التصميم ، وعملية التحكم. تم استخدام برنامج ANSYS Maxwell 3D لتصميم ونمذجة محول العزل عالي التردد وتم تقديم نموذج عملي لمحول العزل عالي التردد من النوع core-type. وتبين من خلال نتائج الدراسة والتحليل لمحول الحالة الصلبة أنه سيكون بديلاً مناسباً للمحول التقليدي الذي يعمل على ترددات عالية.

الكلمات الداله :

محطات القدرة الموزعة ؛ مصادر الطاقة المتجددة ؛ محول الحالة الصلبة ؛ ANSYS Maxwell.