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Design and simulation of a 100 kVA intelligent universal transformer enjoying the voltage ratio of 20kV:380 V

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Abstract

In order to reduce the volume and size of distribution power transformer, precise and extended controlling of transformer output, the conventional transformers are replaced by intelligent universal transformers (IUTs). In this paper, an IUT, typical of Iran national grid, with the voltage ratio of 20kV:380 V is designed and simulated. Regarding the IUT implementation, a cascaded H-bridge inverter (CHB), and a double active bridge (DAB) inverter, along with a three-phase inverter is used. Finally, the proposed IUT is simulated in various conditions

Keywords: Intelligent Universal Transformer (IUT); Control; Converter;

1. Introduction

Throughout the power systems, the electric power is generated in a large scale within conventional power plants. The generated power is transferred through high voltage (HV) transformer toward distribution grids, and then is delivered to customers through the distribution network. So, it is just one direction for the power from producer to customer. Recently, many industrial countries have been restructuring their power systems in different aspects, such as power market creation, and high penetration of renewable energies. Consequently, there are many directions for power flows and the power system operation is becoming complicated. Therefore, it is necessary to use smart infrastructures in the power system in order to achieve an effective and appropriate operational plan[1].

Nowadays, the idea of intelligent universal transformer (IUT) to gain a remote control and bi-directional power control has been proposed. The IUT is capable to handle the output voltage and current, thereby being as the best element in order to connect the distributed generation into the power system. Also, the IUT controls the power flow by which the power system could be operated reliably. Different researches have suggested some topologies for the IUT equipment. By the way, the IUT consists of an AC/DC, a DC/DC, and a DC/AC inverter in addition to a high frequency transformer[2].

Originally, James Brooks used a solid state transformer (SST) in the case of high frequency in 1980[3]. Unfortunately, it did not produced in the large scale because of some limitations. Then, EPRI introduced an SST named intelligent transformer in the U.S. in 2009. It was a 20 kV transformer in which there was a GTO switch and a DC/DC resonance inverter in order to decrease the total active power losses. Afterwards, Maitra proposed a multi-level AC/DC and DC/DC converter in 2009[4]. It was a single directional system which became bi-directional through the change of an active rectifier instead of an inactive one. In [5-7], a 13.8 kV, a 7.2 kV using a CHB inverter are fabricated and simulated. It is worth to say that it was for the first time, which IUT with 20 kV have been designed.

Throughout the Iran national distribution grid, it is usual to employ transformers with characteristics of 20 kV: 380 V in different conditions. The conventional transformer could be replaced by an IUT as long as the input and output voltage of IUT equals to those of conventional transformer. In this paper, an IUT with the voltage ratio of 20kV:380V is presented.

2. Principle of intelligent universal transformer

The use of power electronic converters and various filters in the IUT structure can increase its manufacturing cost and complexity drastically. However, the IUT has some advantages in comparison with conventional transformers. Some benefits of IUT are classified as follows [2]:

- Less size and weight
- Less environmental pollution
- Instant voltage regulation and power factor correction
- Network isolation in the case of contingency
- Active and reactive control capability
- Management of fault current at the HV and low voltage (LV) side
- Power quality increment for any input, including harmonics, and nonlinear loads
- High capacity for voltage variation
- Capable of changing frequency in output and input side
- Capable of DC voltage connection into input and output side
- Voltage compensation capability
- Protection of network capacitors

Prior to this work, the highest voltage level for IUT equals to 13.8 kV. But, for Iran national distribution grid, it is required to implement an IUT with 20 kV voltage level. As the maximum permissible voltage applying on power electronic switchers is 6500 V, the need for a multi-level converter arises.

As previously stated, the IUT is constructed in three sections: AC/DC, DC/DC, DC/AC inverters. In this investigation, the cascaded H-bridge (CHB) inverter is used in order to convert AC voltage to DC voltage. Then, a double active bridge (DAB) inverter is employed as a DC/DC converter. Finally, a conventional inverter is used to change the DC voltage to AC voltage.

In designing stage of CHB and DAB inverters, it is worth to consider that the DC bus voltage does not violate the permissible range. Because, this violation can destroy power electronic switches. So, a safe range, that is 1.05 maximum voltage, is defined in order to protect switchers. So, the number of levels can be formulated as follows [8]:

$$N_m = ceil(\frac{100\times\sqrt{2}\times V_{ph-MV}}{95\times V_{DAB1-\max}}) \tag{1}$$

In this work, for changing 20kV voltage to a 6500 V, QIC6508001 switch is used [9]. Because of this, the number of levels in CHB and DAB, according to (1), is 3.

Fig.1 shows a schematic of the proposed IUT. At first, the phase voltage through a reluctant filter and Three CHB inverters are converted to DC voltage. Then, using a DAB inverter in each level, the DC voltage is converted to a low voltage level. Finally, the DC voltage is changed to the conventional, 3-phase, 380 V voltage level using a traditional three-p.

3. Cascaded H-bridge (CHB) Converter

The CHB converter consists of a cascaded string of many bridge inverters. Fig. 1 illustrates a three-level CHB inverter in which each bridge has a separated DC bus. To create different voltage levels, it is possible to connect two or more bridge inverters in a cascaded way.

A) The frequency of carrier wave and reluctant filter

The carrier wave frequency and the reluctant filter frequency depend on the network features. For example, as the carrier wave frequency increases, the voltage and current harmonic values decrease, thereby reducing the size of reluctant filter. It is worth to pay attention that the carrier wave frequency increment intensifies the amount of switching losses. Also, the reluctant filter size increment subside the amount of current and voltage harmonics. This event causes to increase the investment, and reluctance size and an undesirable voltage drop in inductance filter. Therefore, it is necessary to optimize the amount of reluctant filter and switching frequency in order to avoid excessive system harmonics [8].

B) The CHB controller

In this work, the IUT has a single direction for power injection from the distribution network toward loads. Hence, the CHB controller is responsible to control the output of DC bus voltage. The block diagram of this inverter is shown in Fig. 2. Firstly, the sampling of DC bus voltages is done. Then, the average of samples is compared to the base value. After that, the PI controller determines the inverter current value. The comparison of base value and average value of current results shows in providing the d voltage for pulse width modulation (PWM) through the PI controller.

Similarly, the base current-q, the flowing current-q, and the PI controller can generate the voltage-q. Finally, the base voltage for PWM can be produced by using the dq/abc transfer framework.

It is worth to say that the phase-shift PWM (PS-PWM) strategy switches the inverter in this work. The PS-PWM strategy works based on some sinusoidal carriers with regard to control the three-level CHB inverter. Two triangular carriers are defined and an independent modulation is employed by using a similar reference signal. A 60 degree shift of sinusoidal carrier can make a complete sinusoidal wave for each level.

The output voltage of each level can adopt every voltage value in direct proportion to input voltage value and duty cycle. Although it is possible to determine the average value of voltage levels, shown in Fig. 2, the three-level CHB inverter needs voltage balance between different levels. In other words, different levels must have equal value, because an unbalanced voltage condition can destroy the power transformer and switchers. The PI controller generates a voltage balance factor for each level. Then, the multiply of balance factor by the phase duty cycle specifies the duty cycle for each stage.

4. Double active bridge (DAB) inverter

In order to generate the high-frequency voltage, it is needed to use a bi-directional DAB inverter. The DAB converter comprises of three main parts: DC/AC converter, high-frequency transformer, and the AC / DC inverter as demonstrated in Fig. 4. Furthermore, the number of inverters equals to the number of CHB inverters, or the number of levels of the input inverter. If the number of levels for the input inverter increases, the number of high-frequency transformers and DAB converters increases consequently.

The transferred power is based on the DAB duty cycle. According to the inverter circuit, the DAB power could be calculated as follows[10]:

$$P_{DAB} = \frac{n_{Tr} V_{DAB1} V_{DAB2}}{2 L_{DAB} f_{DAB}} \times D_{DAB}(1 - D_{DAB}) \qquad (2)$$

A) The controller of DAB inverter

In this paper, the DAB converter is operated through PS-PWM switching strategy. In this method, by creating a phase difference between the primary square-shape voltage and the secondary one, the switching could be done.

In Fig. 5, the schematic of DAB inverter is shown. The aim of this inverter is to regulate the output voltage and current. Therefore, there are one voltage loop and current loop in order to control the ϕ phase through PI controller. The ϕ phase is in (0,90) interval which as the phase comes to 90 degree, the transferred power increases. Finally, switching pulses are provided for two DAB inverters. It is worth to say that a controller is needed for each stage of DAB.

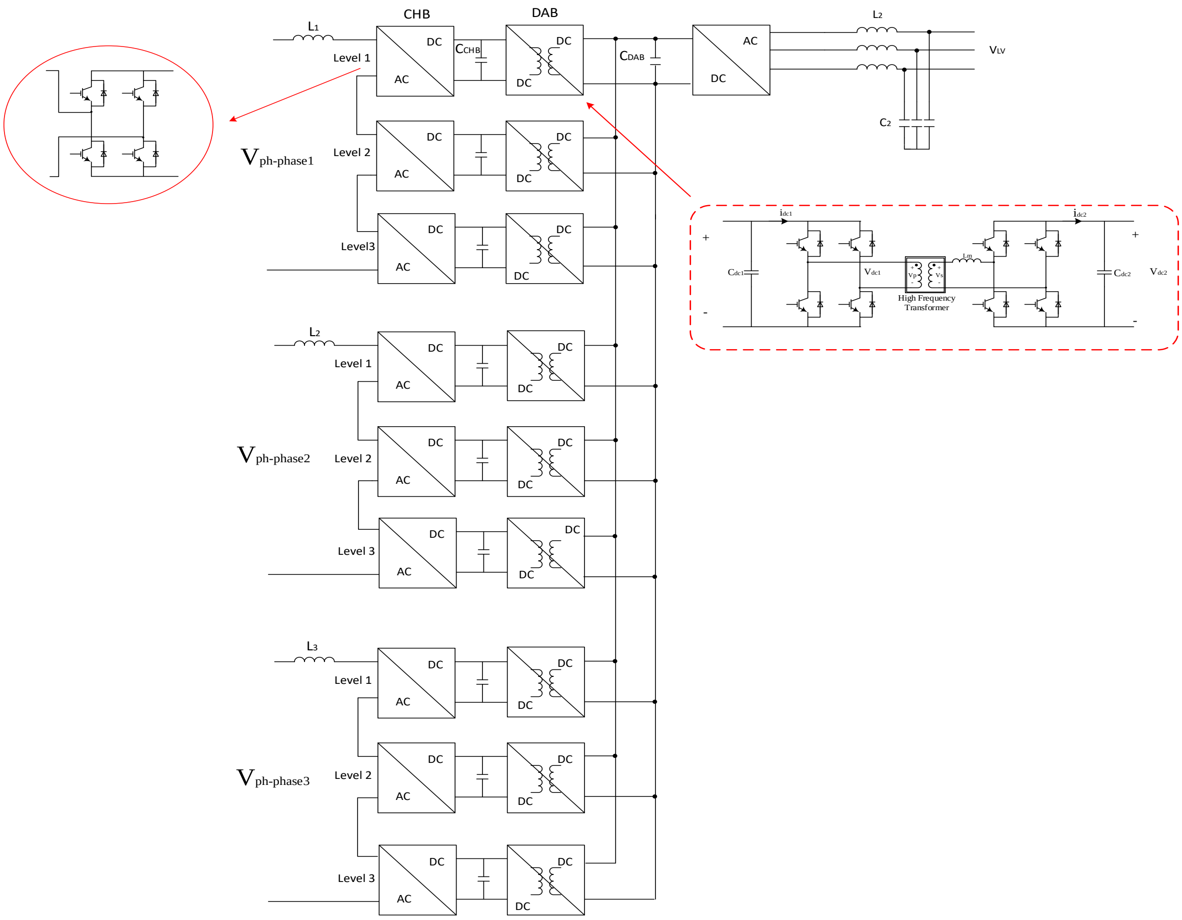

Fig. 1. Architecture of intelligent universal transformer

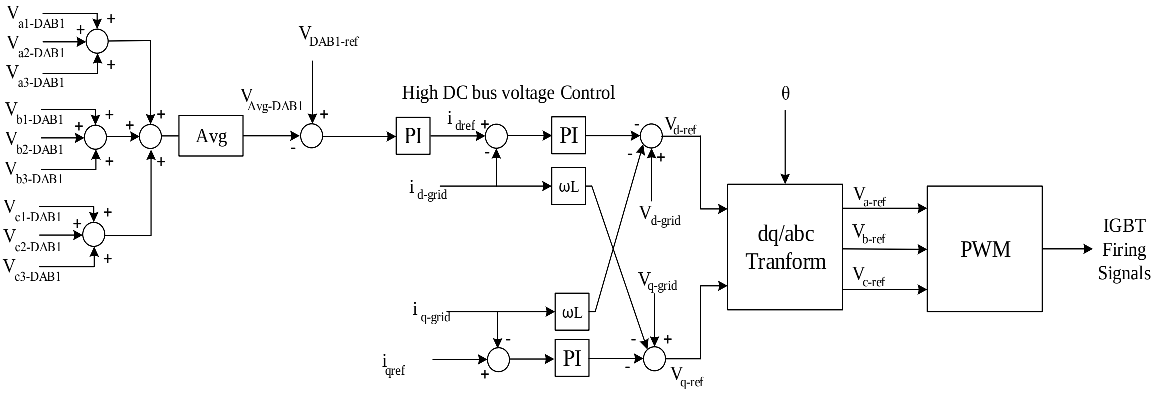

Fig. 2. The contrller of a three-level CHB inverter

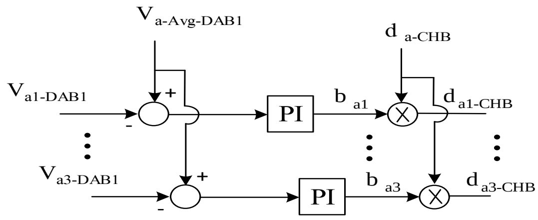

Fig. 3. Voltage balance loop for each phase.

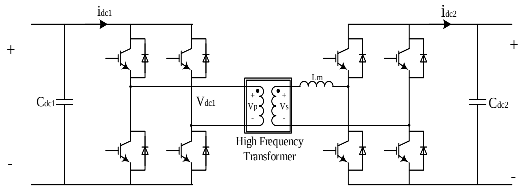

Fig. 4. The DAB inverter

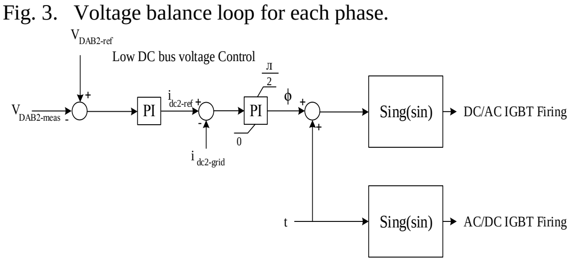

Fig. 5. The controller of DAB inverter.

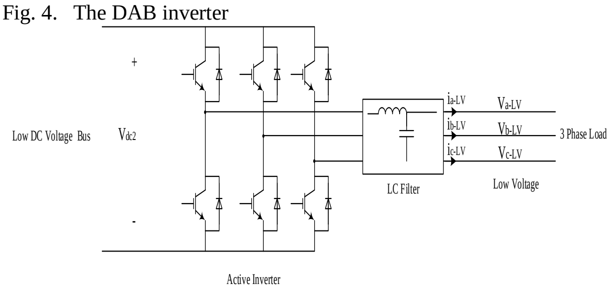

Fig. 6. The conventional inverter schematic.

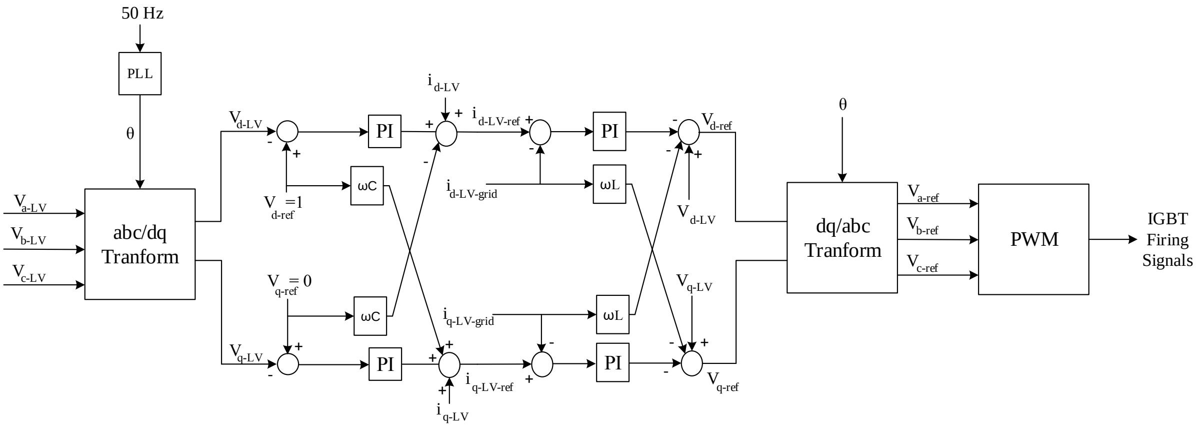

Fig. 7. The conventional 3-phase inverter controlling model

5. The conventional three-phase output inverter (2L-VSC)

In order to change DC voltage into AC voltage, a three-phase inverter with conventional topology is considered. The DC voltage of DAB output in this inverter is converted to three-phase AC voltage. The diagram of the inverter is illustrated in Fig. 6. Also, it is necessary to use a suitable filter at IUT output in order to control active and reactive powers.

A) The controlling of 2L-VSC inverter

Many approaches have been presented concerning the control of conventional three-phase

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inverter based on the type of output filter. In this paper, the controller injects the current to load and regulates the 3-phase output voltage. Therefore, two current and voltage loops handled by PI controller are located according to Fig. 7.

The 3-phase conventional converter, firstly samples from output current and output voltage, then employs dq/abc transfer framework in order to provide measuring parameters for the controller. Further, the 3-phase converter determines the dq voltage variations using the voltage and the current loops. Finally, using the dq/abc transfer framework, a sinusoidal voltage is generated for PWM switching [11].

6. Simulation and Results

To assess the performance of the proposed IUT, the IUT is applied to a case study. The characteristics of the proposed IUT are presented in Table. 1.

Table.1.
The IUT parameters

Size	Symbol	Parameters
200 mH	L_1	The input reluctant filter
10 mF	C_{CHB}	The DC bus capacitor of CHB
22.5 mF	C_{DAB}	The DC bus capacitor of DAB
4 mH	L_2	The inductance of output filter
1.75 mF	C_2	The capacitor of output filter
1 kHz	$F_{CHB\text{-}sw}$	Switching frequency related to 2L-SVC and CHB
10 kHz	$F_{DAB\text{-}sw}$	The switching frequency for DAB
29.8 mH	L_m	Leakage inductance

In this section, the IUT is evaluated in different conditions as follows:

- In the nominal load point
- The active and reactive power output of IUT, respectively.
- Voltage drop in the IUT input
- Single phase to earth fault in the IUT output
- Nominal load point

Fig. 8, and Fig. 9 illustrate the output and input voltage of IUT, respectively. Also, the DC voltage of three levels for one phase is shown in Fig. 10. Furthermore, the active and reactive power flows are demonstrated in Fig. 11. Finally, the harmonics charts for current and voltage of IUT output are shown in Fig. 12 and Fig. 13, respectively.

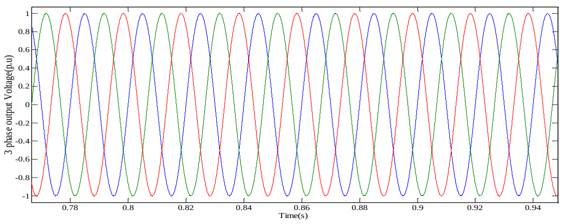

Fig. 8. The output voltage of IUT

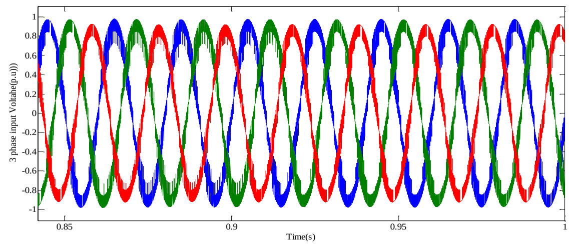

Fig. 9. The input voltage of IUT

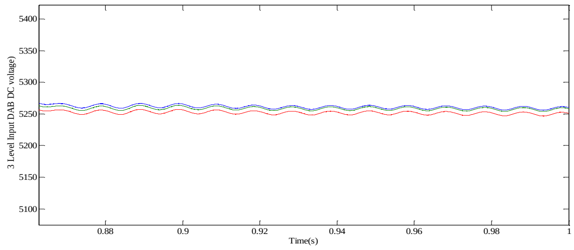

Fig. 10. The voltage of three levels for one phase of DAB

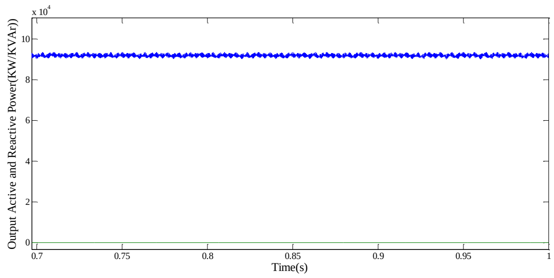

Fig. 11. The active and reactive power of the IUT output

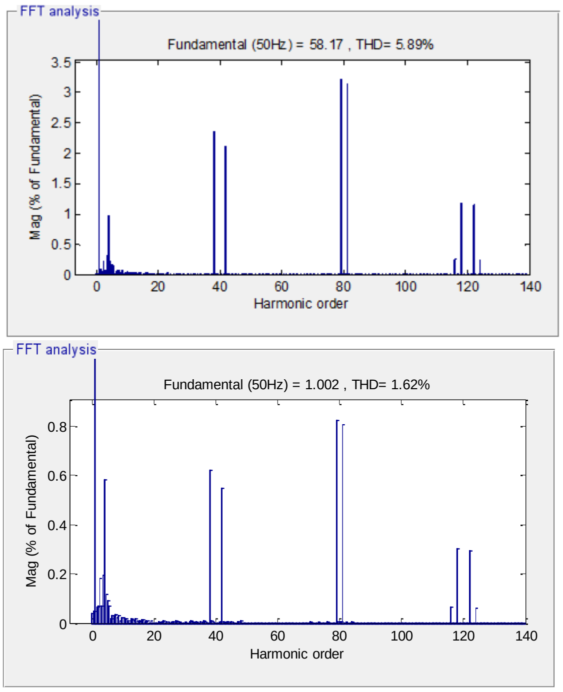

Fig. 12. Output voltage and current THD

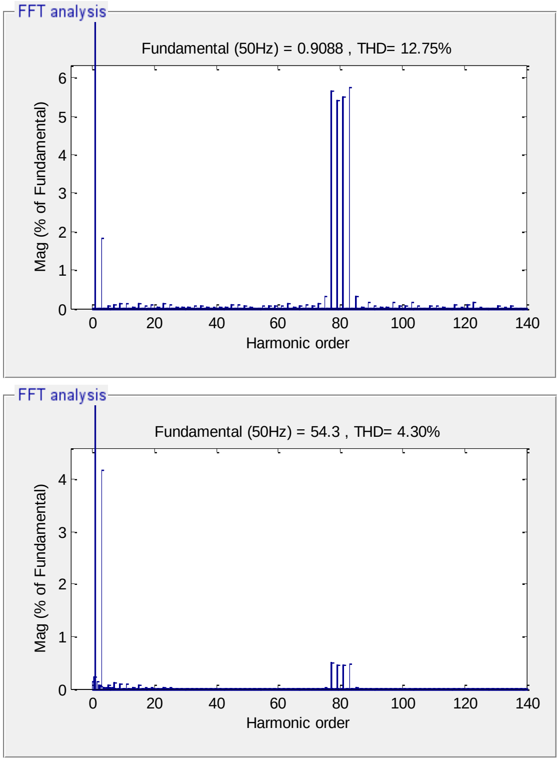

Fig. 13. Input voltage and current THD

As shown, a suitable sinusoidal 3-phase voltage is provided. The THD of current and voltage is less than maximum point, namely 15 percent for 100 kVA, according to IEEE standard.

B) A change in load active and reactive power

In this section, the active and reactive power variation of the IUT output is analyzed. In this case, the active power has a rise equals to 25 kW long after 0.18 second. This increase of power comes along with a peak point of 55 kW at 0.86 second. Also, the output reactive power increases from 2.5 kVar to 4.6 kVar. It is worth to say that the reactive power curve experiences a peak of 4.7 kVar at 0.02 second.

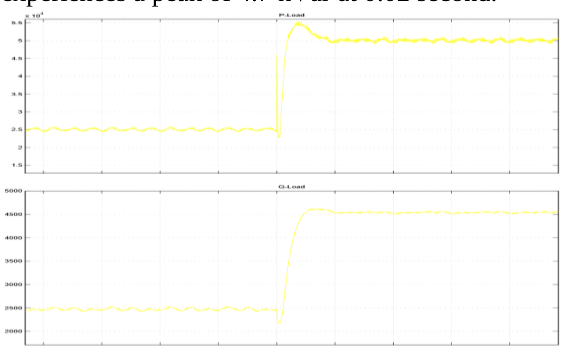

Fig. 14. The active and reactive power diagram of IUT output

C) The results concerning the transformer input voltage

In this case, the input voltage is reduced for 18 kV shown in Fig. 15. This voltage drop is isolated by available inverters of IUT from the output. So, the output voltage of IUT equals to 1 per unit. So, the IUT maintains the voltage quality of customers viably.

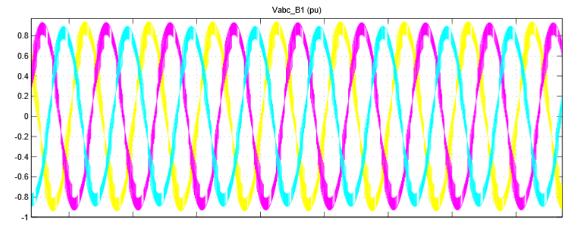

Fig. 15. The input voltage of IUT

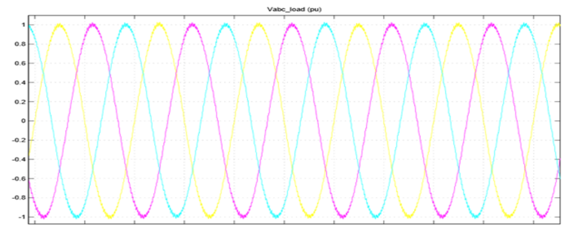

Fig. 16. The output voltage of IUT

D) The results of single phase fault to earth in the IUT output:

In this part, the fault is simulated during 0.06 second interval. In Fig. 17, the output voltage of IUT is shown which the fault time is around 0.2 to 0.26 second. The phase-A which is distinguished by yellow color, during the fault, has a zero value. Then, Fig. 18 shows the 3-phase output current of IUT during the fault. The current of phase-A reaches to 180 A. Because of isolation, there is no way for fault to effect on the IUT output. So, the voltage and current of IUT equals to 1 per unit in the output side.

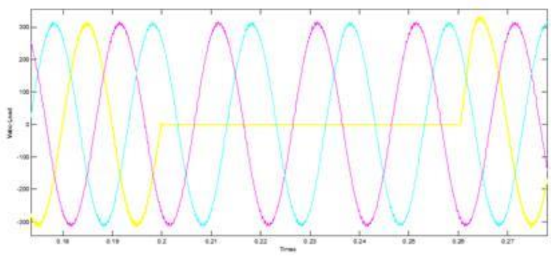

Fig. 17. The output current of IUT

7. Conclusion

In this paper a novel IUT with voltage ratio of 20 kV: 380 V fits in with Iran distribution grid is designed and simulated. This equipment have been analyzed in different conditions. The results show the powerful performance of IUT in comparison to the conventional transformers.

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