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Output DC Voltage Elimination in PWM Converters for Railway Applications

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Abstract—**Auxiliary power supply for modern railway vehicles, powered from the DC catenary line, today is typically connected to the line through an inverter, and an output three-phase transformer. Generally, inverter includes DC component in its output voltage because of difference in switching behaviour of power devices which are used in the power converters. DC component leads to the magnetic field saturation of the transformers, which causes energy loss, and acoustic noise. Therefore, it is necessary to prevent the appearance of DC component on the inverter output. This paper proposes the basic methods used in practice to reduce adverse effects of DC component on the operation of three-phase transformer.**

Keywords—Converter Control, DC/AC converters, Three-phase system, Railway Application.

I. INTRODUCTION

Over the past twenty years a large number of auxiliary power converters with galvanic isolation for use in railway application have been investigated. Different solutions, which differ primarily by the fact that the power supply contact lines are intended, have been used [1]-[3].

In typical DC lines with nominal voltage of 1500 V or 3000 V, Fig. 1, as well as in case of AC supply with DC-link voltage more than 1000 V, auxiliary power converter usually is realized with a three-phase inverter, and a three-phase transformer. On the input side the inverter is connected via input filter to DC catenary line or directly to DC-link of traction converter, while on the output side, a three-phase transformer is connected to inverter [4]. Transformer is used for galvanic isolation of the pulse width modulated (PWM) DC-link voltage, and the on-board power supply.

One important consideration affecting the design of suitable control structure of the inverter is that care must be taken to ensure that operation involves balanced drive to the transformer primary side. Ideal AC power sources do not include DC component. However, at some instances inverter include DC component in its output voltage. When the output voltage contains DC component due to difference of switching behaviour of the switches or other reasons, the DC component is produced in the output of the inverter, and the input of the transformer. The DC current will unbalance the magnetic flux in the transformer, and push the transformer core into saturation on one half of the current cycle as well as large distorted input current, distorted output voltage, and acoustic noise are the result when the component is large enough.

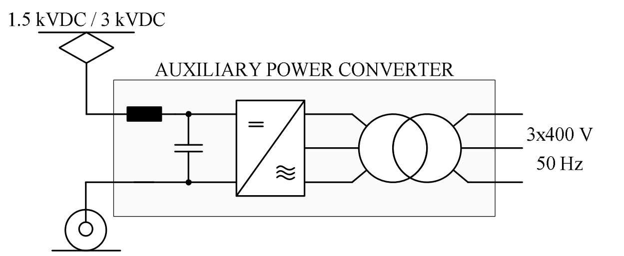

Figure 1. Circuit configuration of auxiliary power converter supplied with the DC line 1500 V or 3000 V.

The basic question is how to reduce DC component on the output of the inverter. In practice few methods to detecting DC component and preventing magnetic field saturation of transformers have been proposed. To choose the most suitable method it is necessary to know switching function, and characteristics of switching devices. This is very important for high power, and high voltage applications, whereas characteristics of switching devices have significant impact on switching delay time. In the next sections, the various methods to reduce DC component are discussed.

II. AUXILIARY POWER CONVERTER WITH GALVANIC ISOLATION

The purpose of this chapter is to give an introduction to converter power configuration, especially in relation to the use of three-phase inverter and three-phase transformer. In configuration in Fig. 1, the power circuit of the converter consists of an input filter, a three-phase inverter, and a three-phase transformer. The input DC line voltage of 1500 V or 3000 V is filtered, and then smoothed in the DC-link circuit. The DC-link voltage is then fed into a semiconductor bridge circuit. A two-level configuration, which is equipped with six insulated gate bipolar transistors (IGBTs), and six freewheeling diodes is selected for the medium voltage application. Medium voltage devices have been recently developed for high power applications using the increased capabilities of power switches like IGBTs, which today are available for a peak blocking capability of 6,5 kV with a DC blocking capability of 3 kV.

In order to feed the AC-loads with a sinusoidal voltage, a sine-wave filter is usually added to the inverter output. The filter converts the square-wave output voltage of the inverter into an on-board voltage of high power-line quality [5], [6]. As a result, users can operate standard equipment, and even laptops when travelling on modern trains.

The inherently low switching frequency of high power converters, limited in a frequency range from 2 kHz to 4 kHz, complicates filter design, which generally results in large filter elements. In order to achieve an almost sinusoidal output voltage, the resonance frequency of the filter has to be well below the lowest harmonic frequency, and well above the fundamental frequency of the output inverter voltage. Therefore, the filter must be tuned between 700 Hz, and 1200 Hz in order to obtain the resonance frequency as distant as possible from the pulse frequency at output of the inverter.

In typical transformer configuration with DC-link voltage up to 1000 V, sine-wave filter is located between the inverter output terminals, and the transformer, Fig. 2. In application with higher DC-link voltage, the filter is located on the secondary side of the transformer, Fig. 3. In practice, the most common solution for DC-link voltage of 1500 V or 3000 V is the filter reactor being integrated in transformer [7]. Therefore the filter capacitor banks are connected directly to the transformer secondary, Fig 4. These transformers are usually performed with an additional magnetic core in order to increase the transformer leakage inductance, Fig. 5. The leakage inductance is defined in a manner that in connection with a capacitor connected, it produces a low-pass filter for the attenuation of the pulse current, and voltage contents.

When the inverter is connected directly to stabilized DC-link voltage, such as DC-link of traction converter, the control system has simpler design. On the other hand, if the inverter is powered by DC line, input voltage is not constant, and varies depending on network load, and distance from the substation. Possible changes in the value of DC supply of 1500 V range from 1000 V to 1800 V, and for supply of 3000 V range from 2000 V to 3600 V. Such large changes in supply network require complex control systems, where in addition to monitoring the inverter output voltage, it is also necessary to monitor input DC-link voltage.

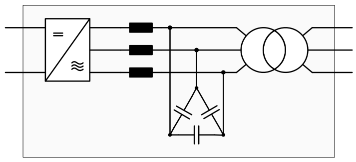

Figure 2. Sine-Wave Filter on the Primary Side of Transformer.

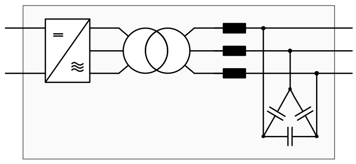

Figure 3. Sine-Wave Filter on the Secondary Side of Transformer.

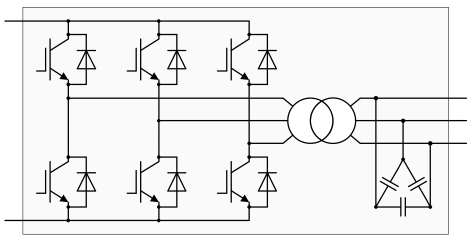

Figure 4. Transformer with Integrated Sine-Wave Filter Reactor.

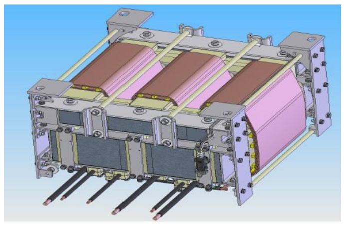

Figure 5. 3D model of Three-Phase Transformer with Additional Magnetic Core (REO INDUCTIVE COMPONENTS).

III. Control Structure

Various control strategies have been proposed in recent works on this type of PWM inverter. Although all control strategies can achieve the same main goals, such as the low harmonic distortion, and near sinusoidal current wave forms, their principles differ. There is no one method of PWM that provides minimal current distortion in the whole range of control. Further performance criteria such as modulation index, range of linear operation, overmodulation, DC component, switching frequency, and switching losses are considered for selection of suitable modulation method. This leads to different types of PWM modulations, which is a basic energy processing technique applied in power converter systems [8]-[10]. The most commonly used PWM methods for three-phase inverters use either the voltage (open-loop) or the current (closed-loop) control [11].

A. *Open-Loop Method*

An open-loop controller, also called a non-feedback controller, is a type of controller which computes its input into a system using only the current state, and its model of the system, Fig. 6. A characteristic of the open-loop controller is that it does not use feedback to determine if its output has achieved the desired goal of the input. This means that the system does not observe the output of the processes it controls. Consequently, a true open-loop system cannot correct any errors it might make, and it also may not compensate for disturbances in the system. Open-loop control is useful for well-defined systems where the relationship between input and the resultant state can be modelled by a mathematical formula.

An open-loop controller is often used in simple processes because of its simplicity, and low-cost, especially in systems where feedback is not critical. In open-loop control there are no internal current control loops, and no PWM modulator block, because the converter switching states are selected by a switching table based on circuit parameters. Generally, to obtain a more accurate or more adaptive control, it is necessary to feed the output of the system back to the input of the controller. This type of system is called a closed-loop system.

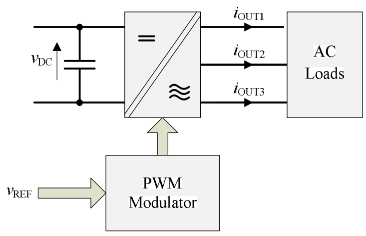

Figure 6. Open-Loop Voltage Control.

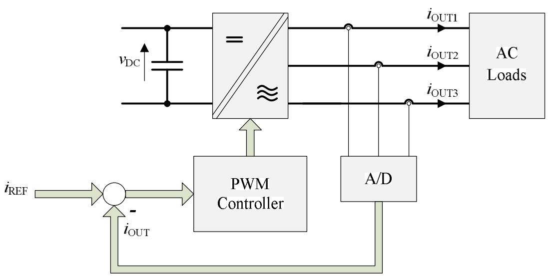

Figure 7. Close-Loop current Control.

B. Closed-Loop Method

In closed-loop controller the output of the system is fed back through a sensor measurement to the reference value. The controller then takes the error (difference) between the reference, and the output to change the inputs to the system, Fig. 7. This kind of controller is a closed-loop controller or feedback controller. Consequently, the performance of the converter system largely depends on the quality of the applied current control strategy.

The closed-loop control, which guarantees high dynamics performance via an internal current control loop, has become particularly popular, and has been constantly developed, and improved. Consequently, the final configuration, and performance of the closed-loop control largely depends on the quality of the applied current control strategy.

For example, determining switching patterns in inverter with stabilized DC-link voltage, and constant AC-loads, in order to achieve a desired constant output three-phase voltage would be a good application of open-loop control. On the other hand, if the DC-link voltage and AC-loads are not predictable, the inverter output voltage might vary as a function of the DC-link voltage as well as the function of the AC-loads, and an open-loop controller would therefore be insufficient to ensure repeatable control of the velocity. An example of this is a system that is required to control inverter at a constant output three-phase voltage. In order for the control system to run inverter at a constant voltage, the switching patterns of the IGBT switches must be adjusted depending on the DC-link voltage, and AC-loads. In this case, a closed-loop control system would be necessary.

C. Dead-Time Effect in Inverter Operation

In Fig. 8 is shown the typical configuration of a phase-leg with IGBTs. In normal operation two IGBTs will be switched on and off one after the other. Having both devices conducting at the same time will result in a rise of current only limited by DC-link stray inductance. Since the IGBT is not an ideal switch, turn-on time and turn-off time are not strictly identical. In order to avoid bridge shoot through it is always recommended to add a so called “interlock delay time” or more popular “dead-time” into the control scheme. With this additional time one IGBT will be always turned off first, and the other will be turned on after dead-time is expired, hence bridge shoot through caused by the unsymmetrical turn on, and turn off time of the IGBT devices can be avoided.

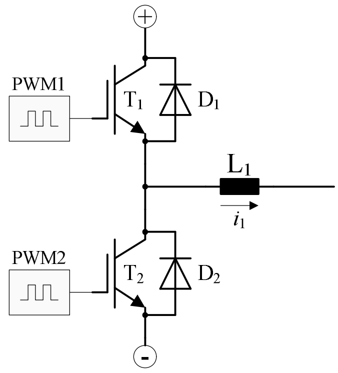

Figure 8. Typical configuration of an inverter leg.

Providing dead-time can on one side avoid bridge shoot through but on the other side it has also adverse effect. Assuming first that output current flows in direction shown on the illustration IGBT T1 switches from ON to OFF, and IGBT T2 switches from OFF to ON after slight dead-time. During effective dead-time both devices are off, and freewheeling diode D2 is conducting output current. So negative DC-link voltage is applied to the output, which is desired here. Consider the other case that T1 switches from OFF to ON, and T2 from ON to OFF, then with current in the same direction D2 still conducts the current during dead-time, so that output voltage will be also negative DC-link voltage, which is undesired here. If we consider output current in the opposite direction, then we will gain a voltage if T1 switches from ON to OFF, and T2 switched from OFF to ON. So in general output voltage, and as a result also output current will be distorted with application of a dead-time. The conclusion can be summarized as follows: during effective dead-time output voltage is determined by the direction of output current but not the control signal [12].

So the process of choosing dead-time is very important, and should be performed very carefully. Dead-time should be chosen on one hand to satisfy the need of avoiding bridge shoot through, on the other hand dead-time should be chosen as small as possible to ensure correct operation of voltage source inverter [13].

IV. Methods for DC Component Elimination at Output Voltage of PWM Inverters

The switching time delay in a PWM inverter has a detrimental effect on inverter operation. It causes a decrease in the fundamental component, an increase in low-order harmonics, and an occurrence of DC component. The inverter DC current will flow in the transformer, which causes the core to saturate easily during alternate half-cycles. A saturated core cannot support the applied voltage. The effect of core saturation using an uncut or ungapped core is shown in Fig. 9 which illustrates the effect on the B-H loop when traversed with a DC bias.

It can be noted that the minor loop remains at one extreme position within the B-H major loop after removal of DC offset. The unfortunate effect of this random minor loop positioning is that when conduction again begins in the transformer winding, flux swing could begin from the extreme, and not from the normal zero axis.

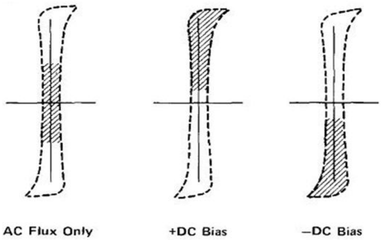

Figure 9. B-H loop with DC bias.

The effect of this is to drive the core into saturation. It is apparent from these views that with a small amount of DC bias, the minor dynamic B-H loop can traverse the major B-H loop from saturation to saturation. The following describes the most commonly used method to reduce DC components of the transformer current.

A. Adding Pre-Resistor to Transformer

This is one of the simplest methods for reducing DC component of the transformer current. The method does not take any measures in control circuit to reduce the DC component of the inverter output voltage. The decrease in DC component is provided by adding a serial resistor on the primary side of transformer.

This method applies to existing solutions within the inverter with output transformer, where it is not possible to make changes in the control circuit, and therefore it is necessary to further reduce the DC component of current transformers. The main drawback of this method is an irreversible energy loss. Typical resistance values for use in railway application are in range of 10 mΩ, while the energy losses on the resistor range between 1 %, and 2 % of total converter power.

B. Air Gap Insertion in Transformer

On the same was as previously method, the air gap insertion method also does not take any measures in control circuit. An air gap insertion into the core has a powerful demagnetizing effect resulting in shearing over the hysteresis loop, and a considerable decrease in permeability of high-permeability materials. The gap increases the effective length of the magnetic path. Fig. 10 shows a comparison of a typical transformer core B-H loop without, and with a gap [14].

When symmetrical PWM voltage is present across primary winding of a transformer without gap, the resulting primary current will be small because of the highly inductive circuit. On the other hand, when an unbalanced DC current flows in the transformer, the core is subjected to a DC magnetizing force resulting in a flux density.

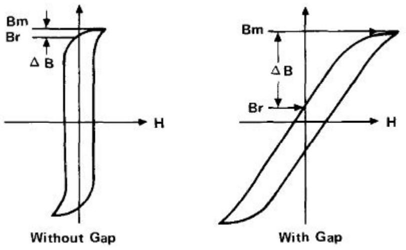

Figure 10. Air gap increases effective length of the magnetic path.

From Fig. 10, it can be seen that the B-H curves depict maximum flux density B_m, and residual flux B_r for ungapped, and gapped cores, and that the useful flux swing is designated ΔB, which is the difference between the two. It will be noted in ungapped configuration that the B_r approaches the B_m, but in gapped configuration, there is a much greater ΔB between them. In either case, when excitation voltage is removed at the peak of the excursion of the B-H loop, flux falls to the B_r point. It is apparent that introducing an air gap reduces the B_r to a lower level, and increases the useful flux density. Therefore insertion of an air gap in the core allows final DC component in transformer.

C. Compensation of Dead-Time Effects

New methods of DC component elimination are based on the active compensation of dead-time effects. Since the dead-time effect is closely related to the load current, it would be natural to make use of the current feedback (more strictly, the feedback of current direction) for the compensation.

Obviously, during the delay time, the output voltage cannot be controlled by drive signals but is determined by the load condition, that is, the direction of the current flow. Although the load condition is subject to change, it can always be said that the voltage deviation due to the time delay opposes the current flow in either direction. Thus, the voltage deviation makes the magnitude of the current to be smaller than expected. This in turn implies one of the important effects of the time delay; the decrease in the effective output voltage of the inverter.

Another important effect is concerned with the harmonics. For each pulse of the output voltage, the voltage deviation shortens or lengthens the pulse duration according to the current direction, and the output voltage cannot be the same with the original PWM control signal. As a natural consequence, there appear undesirable harmonic components in the output voltage, which cause overall distortion of the inverter output waveforms. Furthermore the voltage deviation makes the differences between positive, and negative value of the output current, and therefore the DC current component is generated.

The above discussion clearly shows the detrimental effect of the time delay, and the necessity for the compensation of the dead-time effect. In the following, two methods of compensation are presented [15]-[19].

1) Method I - Modification of Reference Wave

For the sinusoidal subharmonic PWM inverter, the most fundamental realization scheme is the direct comparison of a reference wave with a carrier wave. In such system, the compensation of the dead-time effect is quite simply achieved by modifying the reference wave according to the direction of load current. The circuit in Fig. 11 shows the basic realization principle of the method.

At the first stage of the circuit, a comparator detects the direction of the current. The output of the comparator has the shape of a square wave, which is then added to the reference to generate a modified reference wave.

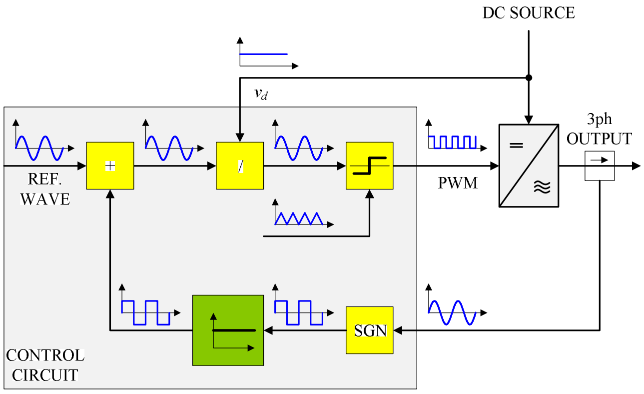

Figure 11. Dead-time compensation circuit with modification of reference waveform.

When the current flows toward the load (positive current), the reference is made more positive, and when the current flows toward the inverter (negative current), the reference is made more negative. By modifying the reference in such manner, the average effect of the time delay is cancelled out, and the fundamental inverter output voltage follows the original reference wave.

The limitation imposed on the circuit in Fig. 11 is that the circuit works on the sinusoidal PWM only, in particular the direct comparison of the reference, and carrier wave.

2) Method II - Compensation with Logic Circuit

Many PWM control strategies rely on the off-line precalculation of the switching patterns, which are usually kept in microprocessor memories. In such systems there is no equivalency to the reference wave of subharmonic modulation which makes it impossible to apply the modification of the reference wave. Therefore, some other means of compensation are necessary.

The synthesis of PWM drive signals is achieved by logical combinations of the original PWM signals in conjunction with the signal that represents the current direction. Method is realized with the circuit in Fig. 12. The converter switching states are selected by a switching table in microprocessor memories based on circuit parameters. The PWM signal has been modified according to the current direction so that the current overcome the reaction of the dead-time effect. Although the reference wave is unchanged, the current waveform shows significant improvement in shape, as well as the increase in magnitude. These improvements are reflected in the frequency spectrum, wherein undesirable harmonics have disappeared, the fundamental component has been increased, and DC component has decreased.

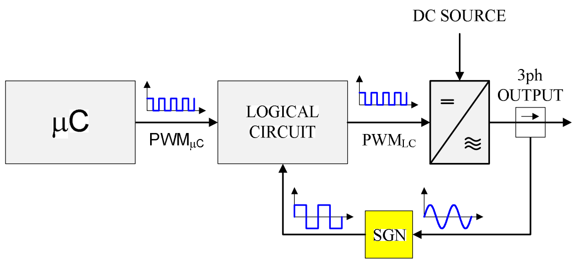

Figure 12. Dead-time compensation with logical combination.

D. DC Component Elimination at Output Voltage

The method is based on the analysis of the output of PWM inverter to determine a ratio between a positive portion, and a negative portion of AC waveform of the inverter output voltage. The determined ratio may be considered to be indicative of an amount of DC component in the output [20].

It must be noted that in a typical inverter output, the DC component represents a very small portion of an overall voltage of the output. Present day converter systems, particularly those used in railway vehicles may require that a DC component is less than 0.1 % of the output AC voltage. The overall DC component represents only a small fraction of the measured voltage, and it is exceedingly difficult to achieve the requisite accuracy.

As it can be seen, there is a need to provide a system for precise quantification of a DC component in AC power produced by the PWM inverter, and then reducing the adverse effects of the DC component. A method for controlling output of an inverter comprises the steps of determining magnitude of a DC component of the inverter output, and commanding the inverter to produce an offsetting DC voltage that is equal in magnitude to the determined DC component, and opposite in polarity from the determined DC component.

Instead of analyzing a full voltage AC waveform to quantify, and control a DC component, a better solution is to employ a measuring technique that substantially segregates the DC component from the full waveform so that the DC component may be precisely quantified. An offsetting opposite-polarity DC component that is equal in magnitude to the determined DC component is delivered to the power system, and the AC-loads are thus provided with AC power that has a reduced DC component. In Fig. 13 is shown a control system for an inverter, illustrated as a block diagram.

Current control is provided with a current control feedback loop which may comprise a current sensor, an analog to digital (A/D) converter, and a current control logic block. Voltage control includes a voltage control loop which may comprise a voltage sensor, an A/D converter, and a voltage control logic block. A detection system is interconnected between the inverter output, and the voltage reference logic block.

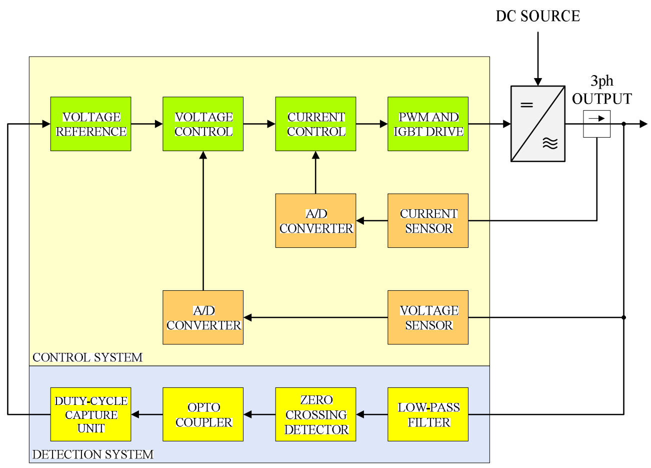

Figure 13. Control system for DC component elimination at output voltage.

The detection system includes a low-pass filter, a zero-crossing detector, an optional opto-coupler, and a duty-cycle capture. The detection system may detect, and quantify any DC component which may be present within the AC power. The duty-capture unit generates an offset voltage signal that is transmitted to the voltage reference. The offset voltage signal is utilized by the voltage reference to produce a DC offset reference that may be equal in magnitude to the detected DC component but opposite in polarity. The DC offset reference is transmitted through the voltage control so that the inverter may be given a command to produce an offsetting DC component equal to the DC offset reference. When the inverter produces such an offsetting DC component, the effect may be to virtually eliminate the detected DC component or at least reduce the DC component to a tolerable, i.e., non-harmful, level.

E. Detecting and Preventing Method for Magnetic Field Saturation of Transformers

Magnetic field saturation of the transformer detecting method is based on a correlation function of exciting current, and effectiveness of DC component in accordance with the value measured by the method. The detection function is designed so it has correlation with the current, which is targeted, and does not have correlation with the other component, for example the load current, the filter capacitor current, and the deformation current of the other windings. As a result, the deformation current is detected from the output current of the inverter, and the output voltage of the inverter is compensated with the result of the detection from the distorted current [21].

V. CONCLUSION

In the process of conversion of DC network supply in the AC-load system, on the inverter output appears DC component. It follows that the AC-loads, in this case the three-phase transformers, must take some DC power, which is not possible, without distorting their functionality. Therefore, the reduction of adverse effects of DC component is an important part of the technical characteristics of the inverter.

Benefits and drawbacks of proposed compensation methods have been discussed along with possible application fields. With passive methods no current sensor and complex control are required but system results with the larger sizes of transformers. On the other hand, active methods have a practical limitation because of the high complexity of control structure. Therefore, benefits of comparison are limited. It would be a challenge to compare experimental results according performances, efficiencies and costs.

Which method will be selected depends on the used control system, on the characteristics of IGBT switches, and IGBT drivers, economic conditions as well as the experience, and preferences of the designers. Data concerning the maximum allowed DC current is one of the designer data upon which are defined the requirements for inverter, and control circuit. Likewise, when inverter is selected, the information regarding the maximum inverter DC current is an essential designer data which enables an appropriate transformer choice.

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