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Simulation and Modeling of a AC-DC Converter Controlled by Pulse Width Modulation Using Soft Switching topology

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Abstract:

This work presents the design, analysis, and simulation of AC-DC converter topology incorporating a voltage source converter (VSC) and a direct converter, connected with medium frequency transformer isolation. A control method is studied by which it is possible to reduce the transformer core losses by only magnetizing the transformer when a Pulse Width Modulation (PWM) pulse should be applied on the AC side of the system. By alternately commutating the two converters it is possible to achieve soft switching conditions for all of the semiconductor elements. Furthermore, it is shown that resonant commutation of the voltage source converter is possible by utilizing the cycloconverter for short circuiting the transformer terminals.

Keywords: AC-DC Converter, medium-frequency transformer, Soft Switching, PWM control.

I. INTRODUCTION:

Isolated AC-DC converters incorporating a voltage source converter (VSC) and a direct converter connected by a medium frequency (MF) transformer, as shown in Fig. 1 [1-3]. The system has been proposed for a wide range of applications including AC-fed propulsion systems and UPS systems. The basic function of this converter concept is that the VSC produces a medium frequency AC voltage that magnetizms the transformer, and this voltage in turn is converted to a desired PWM pattern by the direct controlled. The direct converter can either operate by source commutation [1], [2] in which case the VSC acts as source, or by forced commutation. In case forced commutation is employed the switching losses can be reduced by having the VSC apply zero voltage during the commutations of the direct converter [3], [4]. Methods have also been proposed for reducing the switching losses of the VSC. One way is to have the AC side current freewheel through the direct converter during commutations of the VSC whereby zero-current switching is achieved [2], [5]. Several options exist for the modulation of the two converters. Zero voltage intervals in the output AC voltage can be achieved by letting either the VSC or the direct converter short-circuit its output. Thereby a three-level PWM pattern can be achieved. In case the zero voltage intervals are produced by the direct converter [6], the transformer winding losses are reduced as no current flows through the transformer when the direct converter short-circuits the LF AC output. If, on the other hand, the VSC is controlled to provide the needed zero voltage intervals [3-4], [7-8] the peak transformer flux is reduced as the transformer is only magnetized when a voltage pulse should be applied to the AC side. Thereby the core losses of the transformer can be reduced compared to the case where a square voltage is applied to the transformer. For an MF-transformer the core losses may well dominate over the winding losses and such a control strategy may therefore be preferable. The methods for reducing switching losses mentioned above can generally not be applied to the direct converter and the VSC simultaneously. The switching losses may limit the maximal possible operation frequency of the transformer and thereby reduce the benefits of using an MF transformer. A new concept was presented that employs snubber capacitors in the VSC and a new commutation algorithm in order to allow for soft switching for all semiconductor valves [9]. According to this algorithm the two converters are alternately commutated, thereby mutually setting up the conditions required for soft switching. Furthermore, the system is controlled in such a fashion that the transformer is magnetized by a square wave voltage and zero voltage intervals in the output AC voltage are produced by having the direct converter short circuit its output. In this article the prospects for adapting algorithm to a case where instead the VSC is modulated to produce the zero voltage intervals .In This way, the core losses of the transformer may be considerably reduced[9],[10].

II. PRINCIPLE OF OPERATION:

A. Topology

The topology of the studied converter system is illustrated in Fig. 2. A voltage source converter with two phase legs is connected to one of the windings of a single phase transformer. This converter is equipped with snubber capacitors connected in parallel to each of the semiconductor valves.

The capacitors should be sufficiently large to allow for zero-voltage turn-off of the switches. The other winding of the transformer is connected to a single-phase cycloconverter, which in turn is connected to an inductive line filter. The valves of the cycloconverter do not need any turn-off capability, they may well be realised by thyristors connected in anti-parallel.

B. Commutation cycle

The basic idea behind the proposed method of soft commutation is that the two converters are alternately commutated. Commutation of the VSC reverses the voltage across the transformer thus enabling a source commutation of the cycloconverter which in turn reverses the direction of the current through the transformer. This allows for the next commutation of the VSC etc.

In order to analysis the operation of the converter system in detail a generic commutation cycle involving the two converters will be described. Throughout the analysis the assumption is made that the AC side filter inductor is sufficient to keep the current i_{ac} essentially constant during the commutations. The various states of the cycle and the sequence in which they occur are visualised in Fig. 3.

Mode (1):

The system is initially in this mode, where power is flowing from the DC side to the AC side (the current is flowing through the switches of the voltage source converter). The cycle is start by commutating one of the phase legs of the voltage source converter by turning off the switch that conducts.

Mode (2):

In End mode(1), the current is diverted to the snubber capacitors which leads to recharging of these, and the voltage across the transformer goes down to zero. The turn-off is obviously made at low voltage derivative.

Mode (3):

The current flows through the diode in the opposite valve of the commutating phase leg and it is possible to turn on the switch that is anti-parallel to this diode at zero-voltage and zero-current conditions. At this stage the voltage source converter

Mode (4):

In the next step the other VSC phase leg is commutated in a similar fashion, this leaves the system in a mode (5).

Mode (5):

Where the transformer voltage polarity is reversed and power flows from the AC side to the DC side. Thereby it is possible to commutate the cycloconverter by source commutation where the VSC acts as source. As in the case of the VSC the phase legs of the cycloconverter may be commutated one at a time. The commutation of the first phase leg, mode (6), is started by turning on the valve that does not conduct.

Mode (6):

This valve gradually takes over the current as the voltage supplied by the VSC appears across the leakage inductance of the transformer.

Mode (7):

Finally the initially conducting valve turns off as the current through it goes to zero. Thus the system enters a second state in which the AC output voltage is zero but in this case the current freewheels through the cycloconverter. Subsequently the other phase leg is commutated, mode (8), in the same fashion as the first and thereby the system principally returns to the initial state and the cycle can be repeated.

C. Modulation

By properly adapting the duration of the time intervals during which the system resides in the various states of the commutation cycle it is possible to obtain a desired PWM pattern for the output AC voltage u_{ac}. In practice only a certain subset of the generic commutation cycle is used, depending on the operating conditions and the desired performance of the modulation. This is accomplished by omitting one or several of the active and zero-voltage intervals of the cycle. In this modulation, the zero-voltage interval mode (3) is always omitted. In order to limit the voltage-time area applied to the transformer and thus reduce the core losses it may be more beneficial to instead let the VSC provide the zero-voltage intervals and commutate the cycloconverter phase legs simultaneously. The transformer is only magnetized when a PWM pulse is to be applied to the AC side filter.Fig. 4a-b schematically explains such a modulation method. Two principal cases arise depending on the direction of the instantaneous power flow during a PWM pulse. In case the sign of the desired u_{ac}-voltage pulse coincides with the sign of the AC side current (Fig. 4a), the active mode (5) with power from AC side to DC side is left out. This implies that the commutation of the cycloconverter follows immediately after the commutation of the last VSC phase leg. In the opposite case, i.e. when the desired voltage pulse is of opposite sign compared to the sign of the AC side current (Fig. 4b), instead the commutation of the first VSC phase leg follows directly after the direct converter commutation. Apart from providing a desired PWM pattern on the AC side the modulation algorithm should also ensure proper operation of the transformer. In order to avoid saturation of the transformer core the voltage applied to the transformer must not contain any low frequency or DC components. With the proposed control strategy the transformer voltage pulses correspond to the pulses in u_{ac} with the difference that the polarity of the pulses alternates. Thereby the duration of the pulses applied to the transformer depend on the modulating waveform for the output AC voltage – u_{ac} *. This could theoretically cause a problem as u_{ac} * is an independent input to the modulation algorithm. However, as long as u_{ac} * does not contain any harmonic components close to the operating frequency of the transformer the condition of no low frequency components in u_{tr} will generally be fulfilled.

D. VSC resonant commutation

At low currents the commutation of the VSC may be unduly lengthy as the recharging of the snubber capacitors becomes slower. However, it is possible to achieve a quasi-resonant commutation of the VSC, involving the cycloconverter, in order to solve this problem. Fig. 5 schematically illustrates such a commutation and in Fig. 6 the corresponding principal curve shapes can be found. The process illustrated in the figures replaces mode (2) through mode (4) of the generic commutation cycle. Initially the system is in an active state with instantaneous power flowing from DC side to AC side.

The process is started by switching the cycloconverter so as to provide a current path in the direction of the transformer voltage, stage S1. This voltage appears across the leakage inductance and i_{tr} thus starts increasing linearly. This is allowed to continue until the current has increased by a certain predefined amount, hereafter denoted *enhancement current* i_{enh}. Subsequently the commutation of the VSC phase legs is started by turning off the switch that conducts. This leads to a resonant process S2 governed by the snubber capacitances of the concerned phase leg and the leakage inductance of the transformer. The current continues increasing until the snubber capacitors are fully recharged and the opposite diode takes over the current. The switch anti-parallel to this diode is turned on at zero-voltage and zero-current conditions. At this moment the transformer current amounts to

$$i_{tr,1} = \sqrt{\frac{2.C_s.U_d^2}{L_\lambda} + \left(N i_{ac} + i_{enh}\right)^2}$$

where L_λ is the leakage inductance of the transformer referred to the winding connected to the VSC and N is the turns ratio of the transformer. The transformer voltage as well as the output AC voltage becomes zero with the current $i_{tr,1}$ freewheeling through the VSC, stage S3.When the desired zero-voltage interval commanded by the modulator has expired the other phase leg is commutated in the same way as the first one, stage S4. Thereby a second resonant process, between the snubber capacitors of this phase leg and the leakage inductance, brings down the current through the transformer and recharges the snubber capacitors. Finally, S5, the cycloconverter valves that where turned on in stage S1 turn off as the current through them is forced to zero. The enhancement current that was injected into the transformer in stage S1 can be used to ensure a complete commutation despite losses in the resonance circuit and variations in the AC side current. Note that the time intervals where the polarity of u_{ac} is opposite to the desired one, that occurs during the non-resonant commutation (see Fig. 4), are avoided with the resonant commutation.

III. Simulation and Analysis Study:

In order to test the commutation method a simulation model of an 80 kVA prototype converter has been created in the simulation software Matlab. The key data of the simulated system can be found in table 1. In the simulations, the AC side filter of the converter system is connected to a 400 V_{rms}, 50 Hz single phase AC voltage source u_l whereas the DC side is connected to an ideal DC source. The control logics needed for the commutation were implemented in the form of a number of coupled finite state machines. No closed loop current control was implemented as the objective of the simulations is mainly to study the commutation method. Instead, the amplitude and phase angle of the modulating waveform for u_{ac} were chosen so that the desired power flow was obtained in an open-loop fashion. Circuit simulation in matlab program and the efficiency of converter are shown in Fig.7 and Fig.8, respectively. Fig. 9 display the results from a simulation of a situation in which the converter system operates at rated power with the power flow directed from DC side to AC side. These figures show that:

- The transformer voltage u_{tr}, current i_{tr} during a fraction of a fundamental cycle(transition from resonant to non-resonant commutation of the VSC can be observed when i_{ac} exceeds a preset threshold level of 80 A)

- From an ideal PWM pattern occur during non-resonant commutations of the VSC otherwise u_{ac} follows a three-level PWM pattern (assuming the levels +Ud and 0 in the shown interval).
- A larger perspective of the key signals, the current i_{ac} is essentially sinusoidal and in phase with $u_{l.}$
- The transformer current i_{tr} during the same time interval.
- Finally, the frequency spectrum of i_{ac}. As can be seen the harmonic content is low with the dominant harmonics grouped around even multiples of the transformer operating frequency. No harmonic exceeds one percent of the fundamental.
- The line-side voltage u_{ac} and current i_{ac} is in the same cycle time. The modulating waveform for u_{ac} lays close to $+U_{d/2}$ during the shown time interval. Minor deviations

IV. CONCLUSIONS:

A commutation method for an isolated AC-DC converter that enables bidirectional power flow and galvanic isolation by a medium frequency transformer is presented. It is shown that either (zero-voltage or zero-current switching is possible for all semiconductor elements at all load currents without the need for any auxiliary semiconductor elements. Furthermore it is shown that the transformer peak flux can be minimized by only magnetizing the transformer during the intervals when a voltage pulse should be produced on the AC output of the converter. Simulations verify the feasibility of the concept and indicate that operation with very low line interference is possible.

[redacted]

80 kVA	S	Rated power
700 V	U_d	DC link voltage
4 kHz	f_{tr}	Transformer frequency
12 µH	L_λ	Transformer leakage inductance
1	N	Transformer turns ratio
0.3 µF	C_s	Snubber capacitance (per valve)
2mH (0.31 pu)	L_f	Filter inductor

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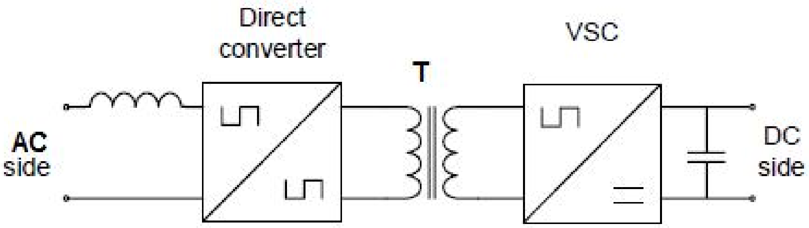


Fig. (1) AC-DC Converter with medium frequency transformer isolation

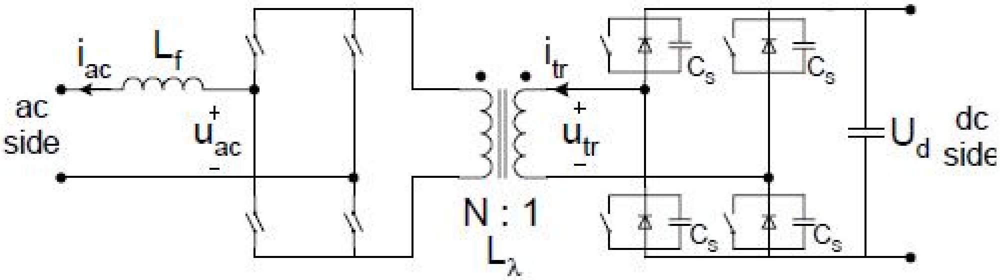
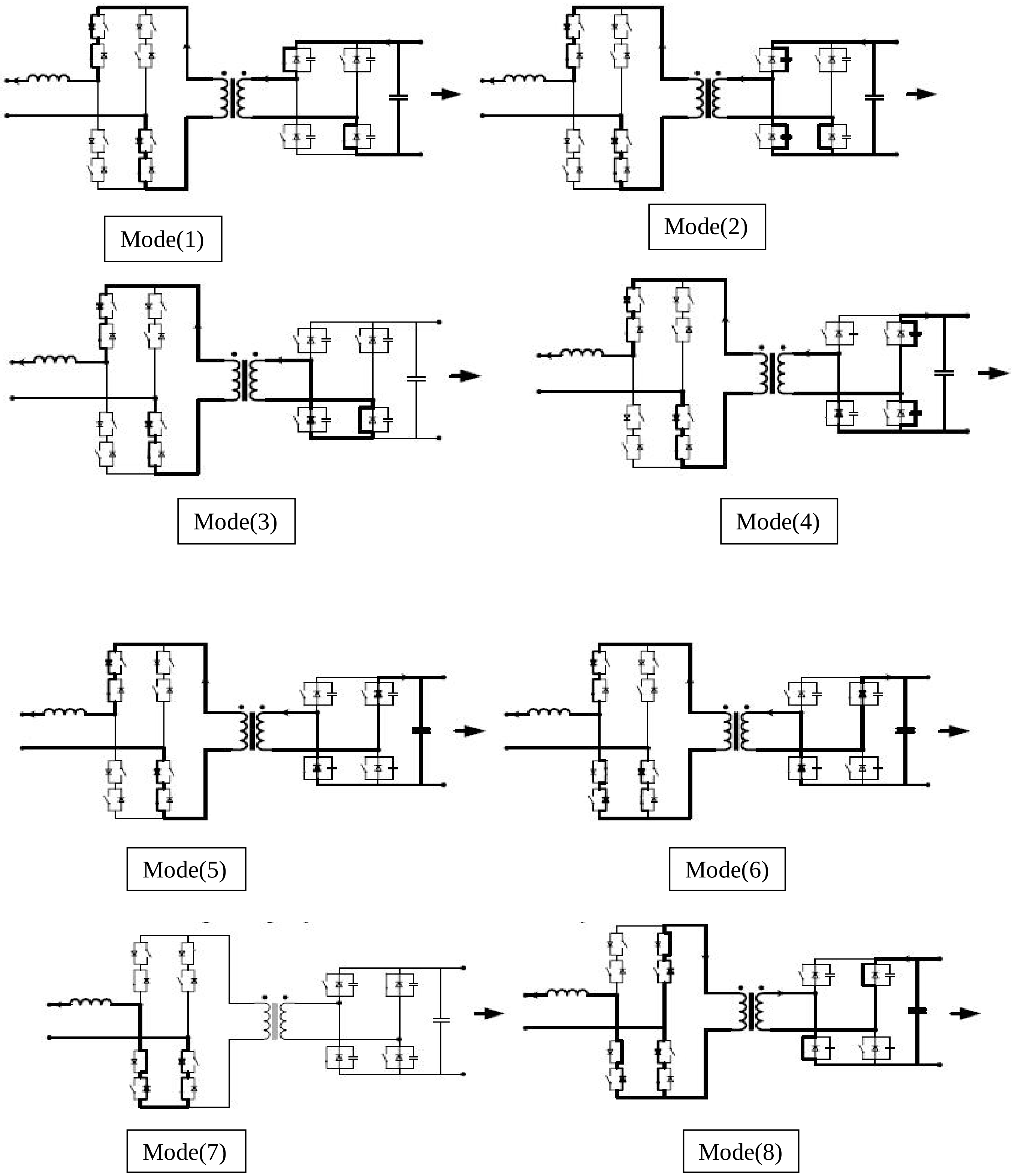


Fig. (2) Topology of the studied converter system



Mode(1)

Mode(2)

Mode(3)

Mode(4)

Mode(5)

Mode(6)

Mode(7)

Mode(8)

Fig. (3) Modes of generic converter

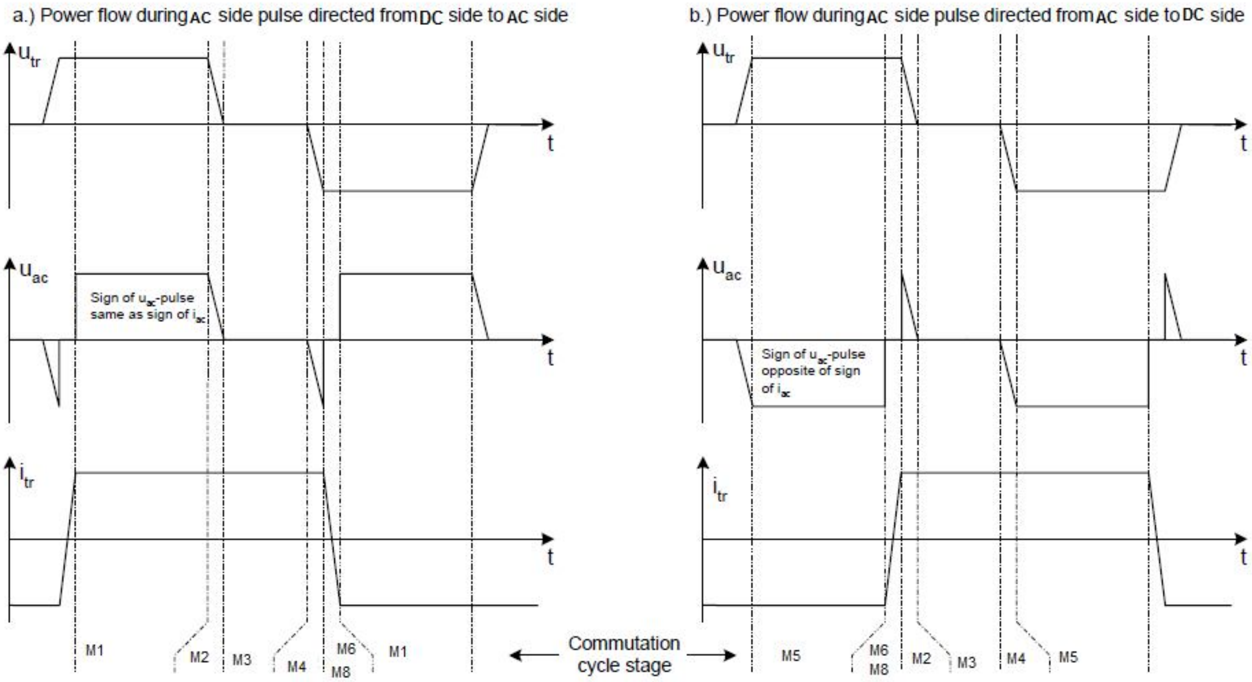


Fig. (4) Modulation for achieving desired AC side pulse patterns for the case where the zero-voltage intervals are provided by the VSC

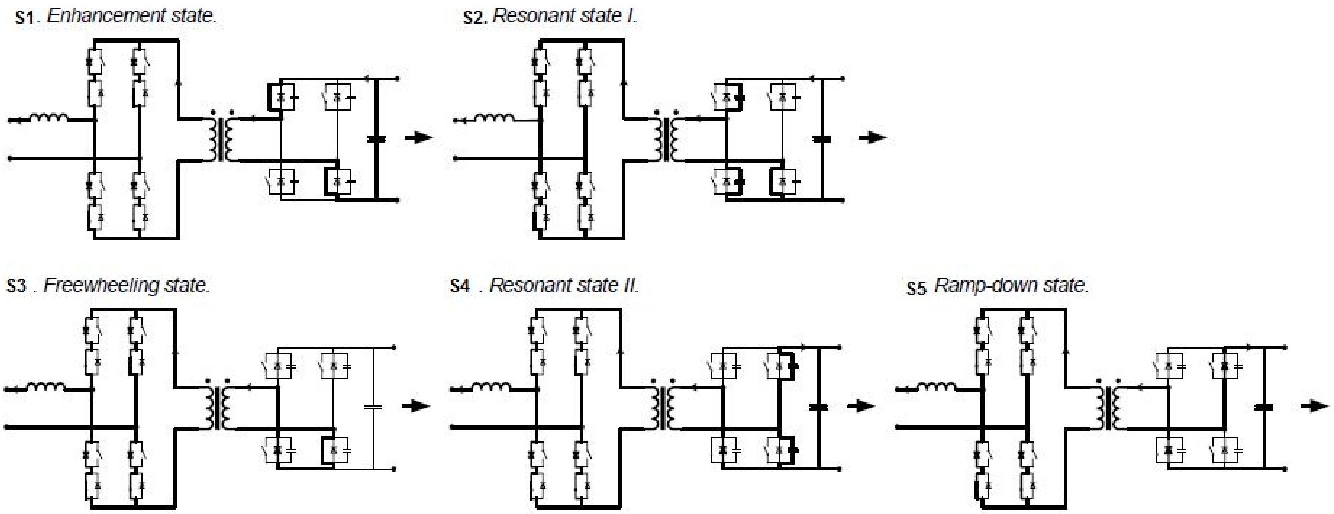


Fig. (5) Resonant Stages for VSC

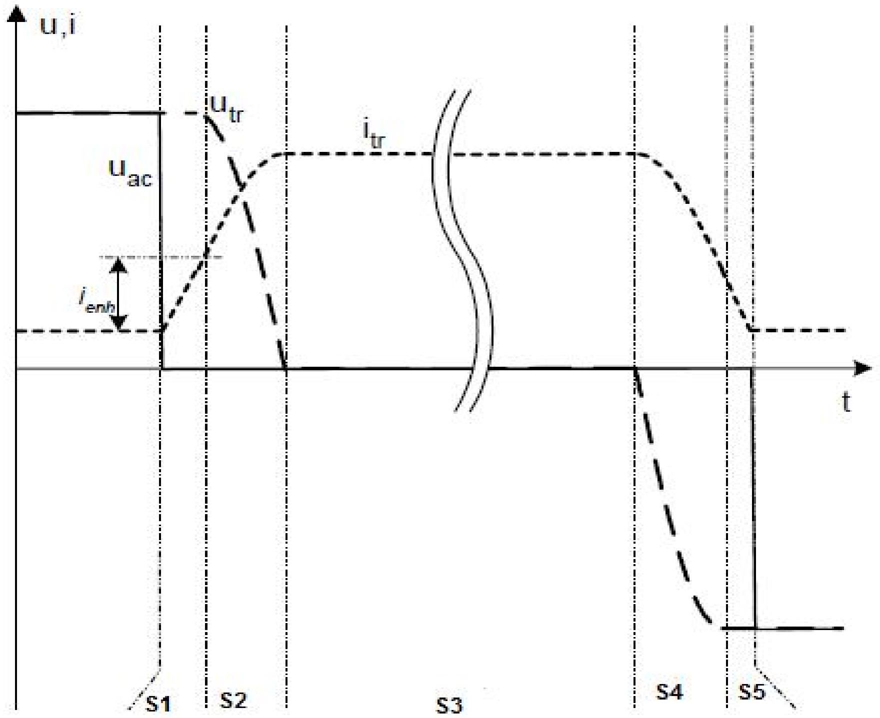


Fig. (6) Resonant commutation of the VSC. Principal curve shapes.
(All quantities referred to the same side of the transformer.)

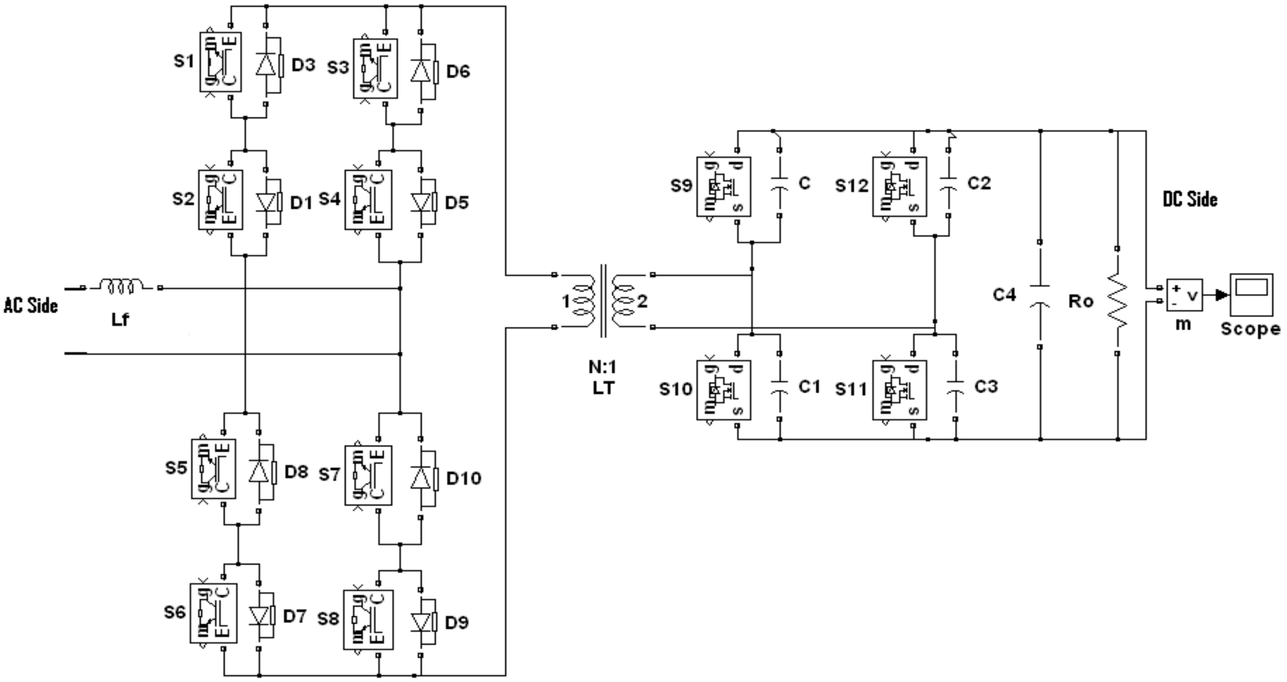


Fig. (7) The Matlab simulation scheme

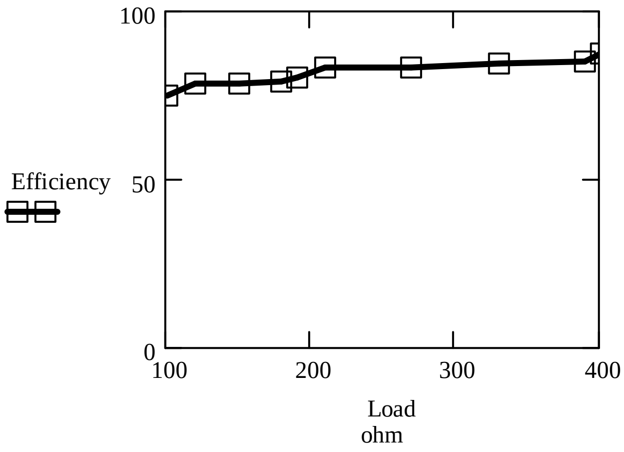
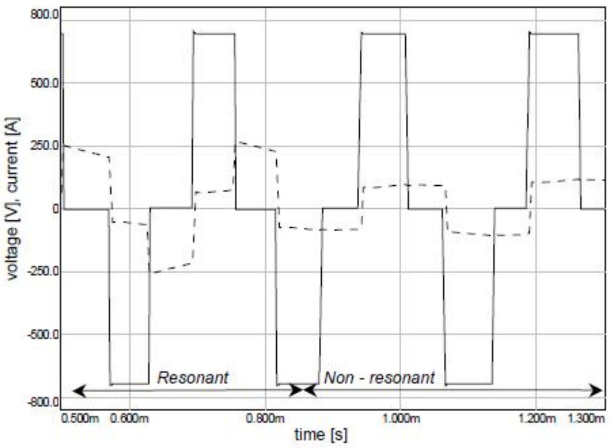
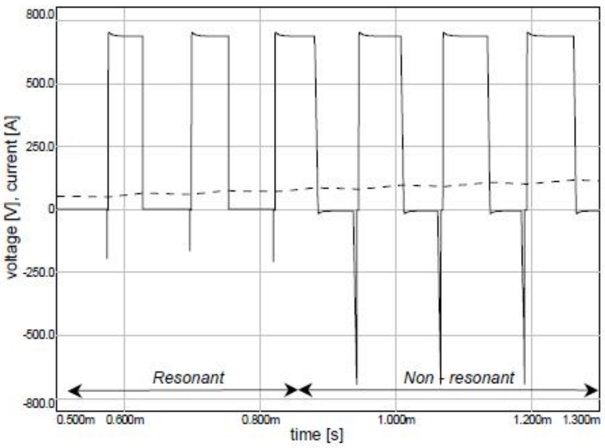
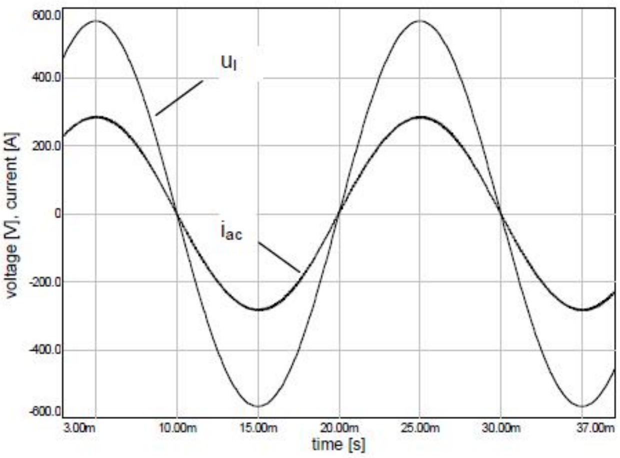
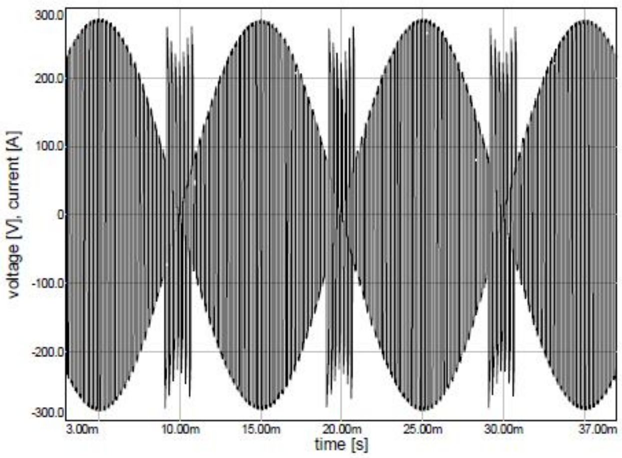


Fig. (8) The efficiency versus the load resistor









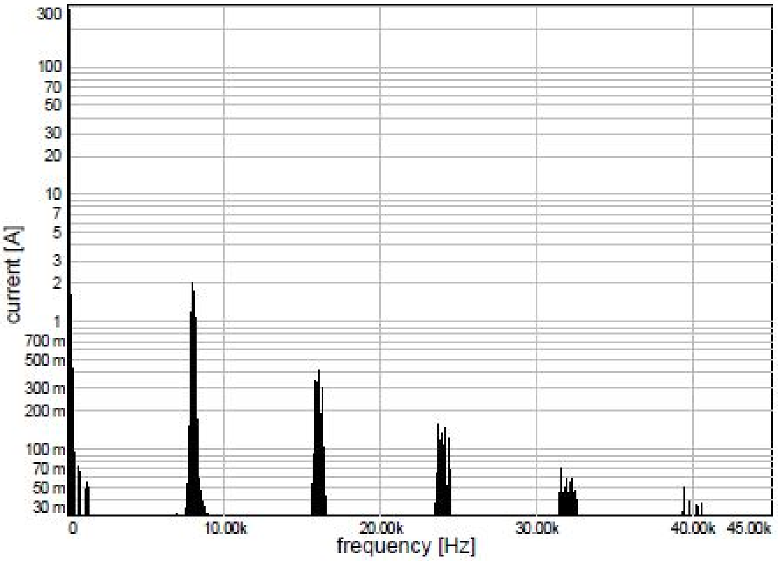


Fig. (9) Simulation of a situation in which the converter system operates at rated power with the power flow directed from DC side to AC side.

محاكاة وأنماط عاكس تيار متناوب- تيار مستمر يسيطر عليه بواسطة تعديل عرض النبضة باستخدام تقنية المفاتيح الناعمة

حسنين عبدالوهاب حنون

مركز الحاسبة الالكترونية - جامعة البصرة

المستخلص:

هذا العمل يمثل تصميم وتحليل ومحاكاة لعاكس تيار متناوب- تيار مستمر الذي هو عبارة عن اتحاد عاكس مصدر الفولتيه وعاكس آخر مربوطين بواسطة محوله ذات تردد متوسط معزولة. طريقة السيطرة تدرس إمكانية اختزال خسائر ألمحوله باستخدام مغناطيسية المحولة ,آلية السيطرة هي تعديل عرض النبضة.

عكس التيار بالتناوب بين العاكسين تمكن من انجاز شرط المفتاح الناعم لكل أجهزة أشباه الموصلات, بالإضافة إلى ذلك توضيح حالة الرنين في جزء عاكس مصدر الفولتيه يكون ممكن بالفائدة من الدائرة القصيرة على أطراف ألمحوله.