A Quasi-Resonant Soft Switching 48-pulse PWM inverter with closed loop current control for the realization of FACTS devices

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Abstract - **This paper discusses a 48-pulse H-bridge PWM inverter which utilizes a quasi-resonant topology that is comprised of a clamping circuit and a resonant circuit, in order to achieve soft switching. The use of a multi-pulse inverter increases the quality of the output whereas the implementation of soft switching technique increases the overall efficiency of the inverter by decreasing switching losses that reach considerable values with the abundant number of switches and a switching frequency of the order of KHz. Furthermore, in order to be able to respond load variations a feedback loop is constructed with a PI controller to realize closed loop current control. The overall system is characterized by a multi-pulse inverter the input voltage of which is not a pure DC but a waveform that occasionally reaches zero level with the help of a quasi-resonant circuit at the source side, and which can keep its current output at a predetermined level by varying the PWM gating signal's duty cycle with the help of a closed loop current control. This system is aimed to be a building block for FACTS devices such as Static Synchronous Series Compensator (SSSC). The motivation of designing a more efficient and dynamic inverter with high power quality is to construct more efficient and effective FACTS devices.**

Keywords – **multi-pulse, PWM inverter, FACTS, soft switching, quasi-resonant, current control**

I. INTRODUCTION

The need for more efficient electricity systems management has given rise to innovative technologies in power generation and transmission. The combined cycle power station is a good example of a new development in power generation and flexible AC transmission systems, FACTS as they are generally known, are new devices that improve transmission systems. Worldwide transmission systems are undergoing continuous changes and restructuring. They are becoming more heavily loaded and are being operated in ways not originally envisioned. Transmission systems must be flexible to react to more diverse generation and load patterns. In addition, the economical utilization of transmission system assets is of vital importance to enable utilities in industrialized countries to remain competitive and to survive. In developing countries, the optimized use of transmission systems investments is also important to support industry, create employment and utilize efficiently scarce economic resources.

Flexible AC Transmission Systems (FACTS) is a technology that responds to these needs. It significantly alters the way transmission systems are developed and controlled together with improvements in asset utilization, system flexibility and system performance. [1]

Various FACTS devices are used to control dynamically the voltage, impedance and phase angle of high voltage AC transmission lines which in turn enables us to operate a transmission line more closely to its thermal capacity thus increasing its transmission capacity, to change the impedance of transmission lines and control the power flow and to damp and filter undesired transients over the transmission system. [2] The most widely known types of these are:

- Static Var Compensators (SVCs)
- Thyristor Controlled Series Compensators (TCSCs)
- Static Synchronous Compensators (STATCOMs)
- Static Synchronous Series Compensator (SSSC) [3]

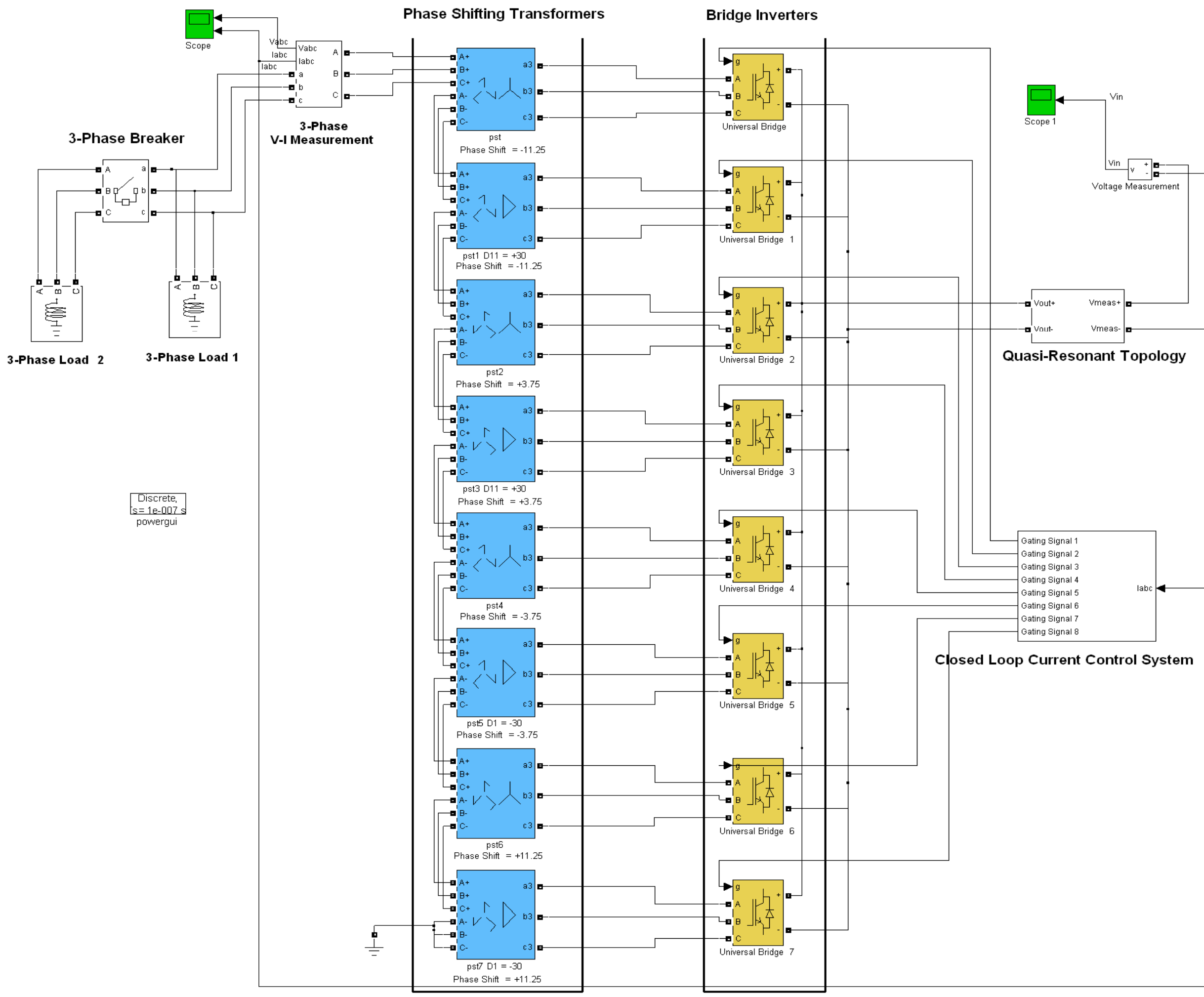

Figure 1. The overall system simulated in MATLAB

All of the above mentioned FACTS devices are based on semi-conductor switches which inevitably bring along power quality and efficiency problems.

In order to improve power quality, which is doubtlessly a very important asset if not the most, multi-pulse inverters are used so that harmonics up to n^{th} order – n being the number of pulses – are automatically eliminated. However with increasing number of switches and switching frequency the power lost in switching attains considerable values. [4] In response to this soft switching techniques are used which ensure that switching takes place when either the component voltage (zero voltage switching) or the component current (zero current switching) is zero. [5]

Considering all these concepts this paper focuses on a 48-pulse PWM inverter with a quasi-resonant topology and a closed loop current control. A multi-pulse inverter is used to improve power quality whereas a soft switching technique is used to eliminate the power loss on switches. A closed loop current control implementing abc-to-dq coordinates transformation and a PI controller is included to sense the load variations and take necessary precautions to keep the current at a desired level.

Following the organization of the paper; firstly the analysis of the system, theory of operation and some key design considerations such as details about the phase shift of the gate pulse patterns as well as the configuration of the magnetic coupling circuit and the phase shifting transformers, resonance frequency, closed loop current control strategy are studied. Then this model is simulated in MATLAB to verify proper operation. Resulting waveforms including output voltages, currents and control signals are also presented to show the operation of the system and its response to changes.

Finally, an FFT analysis is performed on the output current to see the harmonic components and total harmonic distortion (THD).

II. SYSTEM CONFIGURATION

The system shown above in Figure 1 is the combination of three distinct modules with distinct tasks. These are;

a. 48-pulse inverter which inherently filters out the harmonic components up to 47^{th} order and outputs a low-THD, high quality waveform

b. DC supply with Quasi-resonant topology which is a deviated DC supply in the sense that the output of this supply is not a constant dc value but rather a dc value that occasionally goes down to zero whenever the resonance is triggered. This is useful in realization of zero voltage switching technique to reduce switching losses over the semi-conductor switches

c. Current Control Feedback system and PWM generator which is used to generate the PWM signals to trigger the inverter switches, then measure the output voltage and compare it to a pre-determined value and finally adjust PWM gating signals such that the output obtained complies with the pre-determined value. Apart from this the closed loop current control enables the inverter topology to feed variable loads by reacting to load variations.

Overall system is a combination of these three modules which are interconnected to each other and expected to operate in harmony so as to get the desired output. 48-pulse inverter constitutes the backbone of the system by performing DC/AC conversion with low harmonic distortion whereas DC supply with quasi-resonant topology contributes by realizing soft switching and closed loop current control topology contributes by controlling the output current with PWM gating signals.

a. 48-pulse inverter

Eight 6-pulse inverters are combined to obtain a 48-pulse with the purpose of reducing harmonic content. Table 1 shows the values of phase shifts which are applied to the inverter voltages in two steps, namely in firing pulses and in Zig-zag transformers, to create a 48-pulse waveform at the output with the harmonic content in the order of n= 48m±1, where m= 0, 1, 2,… [6, 7]

TABLE 1
PHASE SHIFTS FOR A 48-PULSE VSI

Coupling Transformer	Gate Pulse Pattern	Phase Shifting Transformer
Y – Y	$+11.25^o$	-11.25^o
Δ – Y	-18.75^o	-11.25^o
Y – Y	-3.75^o	$+3.75^o$
Δ – Y	-33.75^o	$+3.75^o$
Y – Y	$+3.75^o$	-3.75^o
Δ – Y	-26.25^o	-3.75^o
Y – Y	-11.25^o	$+11.25^o$
Δ – Y	-41.25^o	$+11.25^o$

The secondary sides of the coupling transformers are connected in series to sum the output voltages of individual VSIs and obtain a multi-pulse phase voltage which can be expressed mathematically as follows:

$$V_{ab_{48}}(t) = 8 \sum_{m=1}^{\infty} V_{ab_m} \sin\left(m\omega t + 18.75^\circ m + 11.25^\circ x\right) \quad (1)$$

$$V_{an_{48}}(t) = \frac{8}{\sqrt{3}} \sum_{m=1}^{\infty} V_{ab_m} \sin\left(m\omega t + 18.75^\circ m - 18.75^\circ x\right) \quad (2)$$

$$\forall m = 48r \pm 1,\ r = 1, 2, ...$$

Both equations (1) and (2) which are phase-to-phase and phase-to-neutral voltage representations, respectively, show that harmonics up to 47^{th} order are inherently filtered.

b. Quasi-Resonant Topology

Figure 2 shows the quasi-resonant topology used in the system. It is used to bring the input voltage to zero occasionally so that IGBTs in inverters can turn-on and/or turn-off while Zero Voltage Switching conditions are satisfied.

In traditional dc link voltage inverter, a large capacitor in excess of hundreds of microfarads is normally used to provide a smooth dc voltage for the power inverter. As the energy stored in large capacitor is considerable, it is not desirable to pull the voltage of a large capacitor down to zero frequently because the energy involved in the resonant process is large, leading to excessive conduction loss in the resonant circuit and requirement of high current ratings for the power devices in the quasi-resonant circuit. [8]

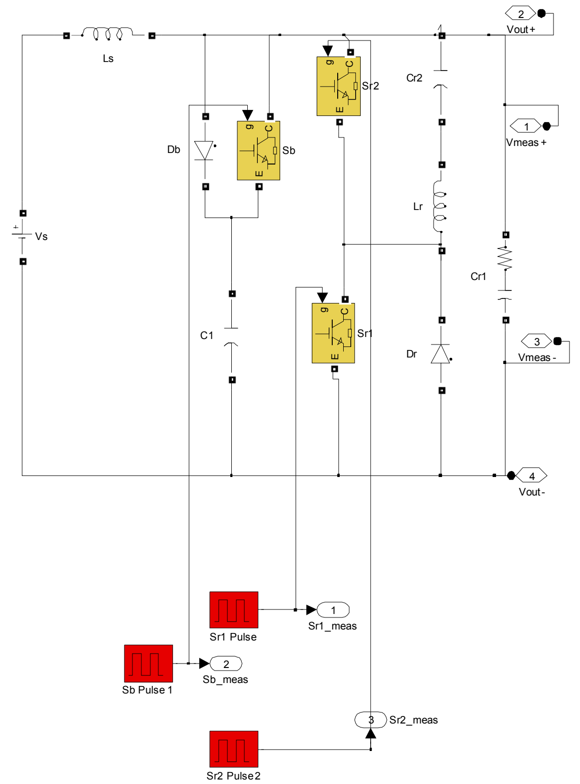

Figure 2. Quasi-Resonant Topology

On the contrary in this circuit a relatively smaller capacitor, namely Cr1, is used. During non-switching periods of the inverter Cr1 is in parallel with C1, which provides the voltage smoothing function. Just before each inverter switching, the dc link voltage needs to be pulled down to zero for ZVS. First C1 is unclamped from the circuit and the voltage on the small capacitor is pulled down to zero. [8] Thus a faster and more efficient resonance is achieved.

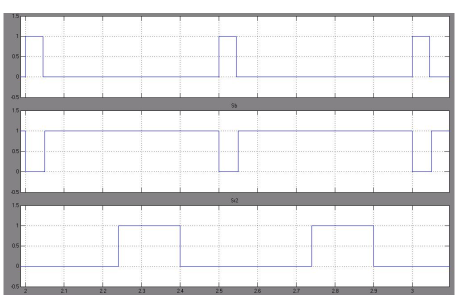

Figure 3. Sb, Sr1 and Sr2 pulses

When appropriate Sb, Sr1 and Sr2 pulses are supplied, as shown in Figure 3, this circuit operates in five different modes. In the first mode Cr1 is in parallel with C1 and charged to a DC value, then in second mode resonance is triggered, C1 is unclamped and Cr1 discharges over Cr2 and Lr. Third operation mode is when the voltage over Cr1discharges completely and stays zero while the inverter switching(s) is(are) performed. In the fourth and fifth operation modes voltages over Cr1 and Cr2 are arranged for the next resonance. The voltages observed over Cr1 and Cr2 are given in Figure 4. It is obvious that the period between t2 and t3 is when Zero Voltage Switching is realized. [8]

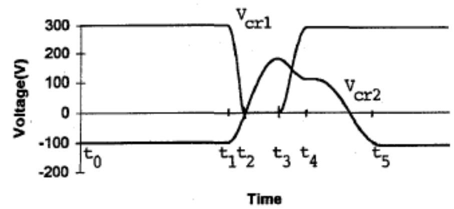

Figure 4. Resonance Capacitor Voltages

Control of the circuit is realized with Sb, Sr1 and Sr2 pulses. Basically these pulses first unclamp the large capacitor C1 from the circuit, and then trigger the resonance. The operation frequency of these control signals is set to 200 KHz meaning that the input voltage is pulled down to zero once in every 5 µseconds. This value is a hundred-fold of PWM generator's operation frequency and thus is sufficient to ensure the realization of zero voltage switching. Once the resonance is triggered the resonance circuit is composed of Cr1, Cr2 and Lr. Considering their values are:

$$Cr1 = 4.7 \times 10^{-9}\ F$$
$$Cr2 = 6.7 \times 10^{-9}\ F$$
$$Lr = 8 \times 10^{-7}\ H$$

the resonance frequency can be calculated from the equation:

$$2*pi*f_{resonance} = 1 / (Lr*Ceq)^{1/2} \qquad (3)$$

where Ceq = Cr1 * Cr2 / (Cr1+Cr2)

The resonance frequency is worked out to be 21.28 MHz which is high enough to ensure complete discharge before the states of control signals change.

c. Closed loop control- feedback loop

The implemented feedback loop makes use of Park transformation on the measured three-phase output currents. This conversion is also referred to as abc-to-dq transformation and used to convert the measured currents to *rotating synchronous coordinates* d-q. Thanks to the coordinate transformations id and iq are dc components thus it is more convenient to perform calculations. [9] The following equations are used for the said transformation:

Vd = 2/3*[Va*sin(wt) + Vb*sin(wt-2pi/3) + Vc*sin(wt+2pi/3)] (4)

Vq = 2/3*[Va*cos(wt)+Vb*cos(wt-2pi/3) + Vc*cos(wt+2pi/3)] (5)

Vo = 1/3*[Va + Vb + Vc] (6)

Once the calculation is performed and new modulation index and new set of gate pulses are worked out reverse Park transformation is realized with the help of following equations;

Va = [Vd*sin(wt) + Vq*cos(wt) + Vo] (7)

Vb = [Vd*sin(wt-2pi/3) + Vq*cos(wt-2pi/3) +Vo] (8)

Vc = [Vd*sin(wt+2pi/3) + Vq*cos(wt+2pi/3) +Vo] (9)

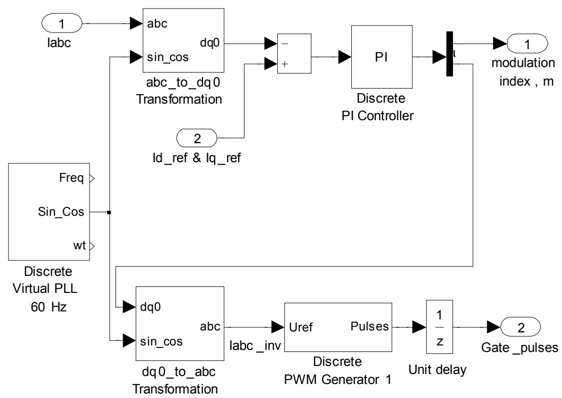

Figure 5. Feedback loop for current control

As it can be seen in Figure 5, after applying Park transformation the measured three-phase currents are fed to PI controller along with reference Id and Iq signals. PI controller outputs new modulation index m and Id-Iq values which are transformed back to abc coordinates and used to generate new PWM gate pulses.

This closed loop current control enables the system to respond expected and/or unexpected load variations by modifying the modulation index and sine waves used for the generation of PWM signals to keep the output current at a predetermined value.

III. SIMULATION RESULTS

The system explained in the previous section is simulated in order to verify proper 48-pulse generation, soft switching and current control.

PWM generator is set to 2Khz carrier frequency. Sine wave supplied by the current control loop has 60 Hz frequency.

DC supply in the quasi-resonant circuit has 750 Vdc with resonance and 48-pulse topology a much higher value is observed at the output.

Two inductive loads are connected in parallel one of which is connected to the system at t=0.05 whereas the other one always stays connected. This helps in judging the closed-loop current control performance.

When the simulation is performed in MATLAB the output waveform shown in Figure 6, is obtained:

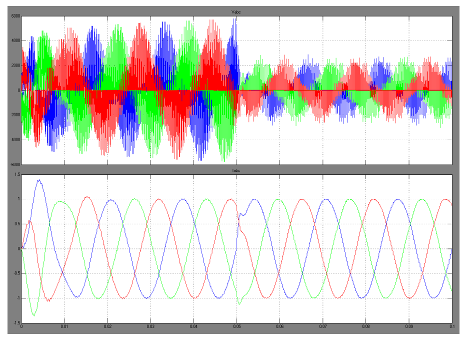
Figure 6. Output Voltage and Current (Vabc & Iabc)

It is worthy to note here that the change in the inverter output voltage occurs at t=0.05 due to the change in gating signals in order to keep the load current at 1.0 pu value.

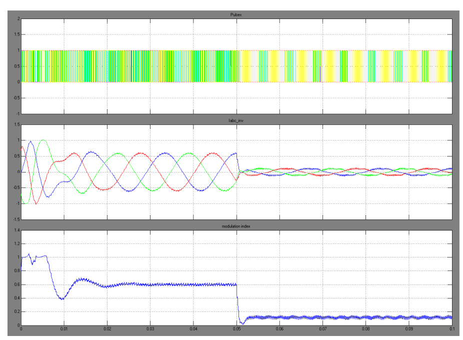
Figure 7. PWM signals, Iabc_inv, modulation index

Figure 7 shows one set of PWM signals, Iabc_inv signal output of the current regulator which is eventually used to generate PWM gating signals and modulation index m. The change in the PWM signal's pattern, Iabc_inv signal's amplitude and modulation index due to the change in load can be clearly seen.

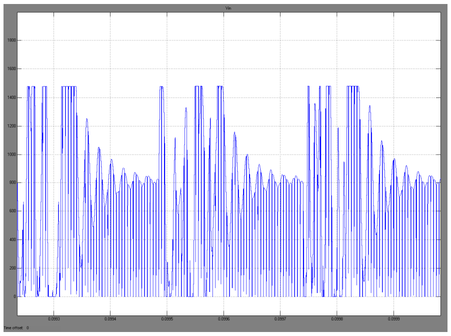

Figure 8. Input Voltage (Quasi-resonant topology's output voltage)

Quasi-resonant circuit operates and pulls the inverter voltage once in every 5 µseconds. With the effect of freewheeling diodes of bridge inverters sometimes the voltage prematurely returns back to zero as shown in Figure 8.

Finally FFT analyses of two states, i.e. before and after the secondary load is taken to the system are given below in Figure 9. The analysis is performed up to 40^{th} level, 2400 Hz. The resulting THD values are relatively higher for a 48-pulse inverter; this fact is caused by the awkward input voltage supplied by quasi-resonant topology.

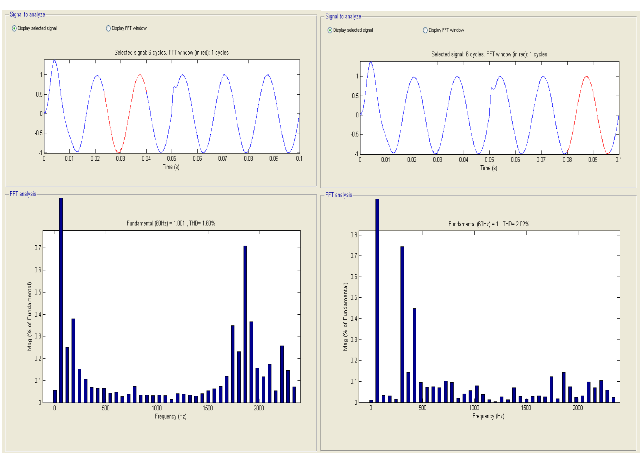

Figure 9. FFT analysis of output current (before and after t =0.05)

IV. CONCLUSION

This paper presents a 48-pulse PWM inverter constructed with eight individual IGBT bridge inverters and equipped with a quasi-resonant topology at the source side and with a closed loop current control at the load side in order to respond to two of the main problems in power electronics which are, respectively, high switching losses and current control in case of large load variations.

According to simulation results the system under consideration operates satisfactorily, including all of its sub-modules meaning that a more efficient multi-pulse inverter has been successfully designed and simulated. The next step that should be taken is to do the hardware work of the newly designed system. However it is worthy to note that MATLAB implements ideal switching on IGBTs so soft switching phenomena should be considered with care when the system is implemented.

V. REFERENCES

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