# Novel Control Methods Applied to a Series Loaded Resonant Converter

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*Abstract*— **Load resonant converter topologies are very popular and used to increase circuit switching speeds, allowing the cost of circuit magnetics to be reduced, while still keeping switching losses to a minimum. In this paper a new open loop and close loop control method for 2.1 kW Series Loaded Resonant DC-DC converter operated in above resonant mode is presented. A voltage controlled oscillator (VCO) is used to regulate the DC output voltage of converter in open loop. The control circuit used to regulate the output voltage of SLR converter is frequency modulation technique in which switching frequency of the converter is varied to regulate the output voltage. The close loop variable frequency control mainly consists of feedback loop and PI regulator with VCO. VCO is a voltage-to-frequency converter used to convert error in output voltage in change of frequency to control the voltage in close loop system. The simulation results for both open loop and close loop control methods are also presented in this paper to verify the control concept.**

***Index Terms*—Series Loaded Resonant Converter, Voltage Controlled Oscillator (VCO), open loop control and close loop control.**

## I. INTRODUCTION

The Series Loaded Resonant (SLR) Converter finds application in DC–DC converters as a preferred resonant converter topology for high power DC power supplies because of its simple structure, buck mode of operation, easy design procedure and higher part of load efficiency [1]. As in resonant applications half bridge topology is chosen for high power application because it costs less, switching losses are less due to two switches only and produce less EMI compared to full bridge. In higher frequency applications of high power DC-DC converters, IGBT is used as Resonant Switch because of fast switching, low power gate drive and lower conduction losses [2] [3].

With the use of IGBTs as power switches the proposed converter is operated in above resonant mode. At higher power levels and higher conversion frequencies, the specific choice of ZVS or ZCS depends mainly on the IGBT turn-on and turn-off dynamics. The turn-on transients of the IGBT are greatly affected by the di/dt while the turn-off transients are affected by the dv/dt across the device. This proposed converter operated with ZCS turn on and ZVS turn off which is helpful to reduce effects of turn-on transients due to high di/dt and turn-off transients due to high dv/dt, so switching losses are considerably reduced [4]. Due to reduction of switching losses it is easily applicable to high frequency, high power applications.

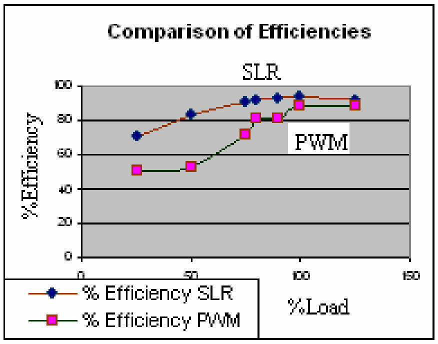

Fig.1. Comparison of efficiencies

Fig1 shows the efficiency comparison of SLR with conventional PWM converter through simulation results. The comparison shows that it is possible to achieve more than 4-5% of efficiency at full load compared to conventional PWM converter.

Tight regulation of output voltage is important for SLR converter and for the regulation of DC output voltage frequency modulation technique is widely used because the fixed frequency control does not actually regulate the voltage gain. The basic frequency curve is shown in Fig 2; dealing with characteristics of SLR circuit, the resonant tank impedance depends on the frequency of operation. For a given applied input voltage and a load resistance, DC output voltage Vo can be regulated by controlling the switching frequency fs. As per Q-curve the control locus for the frequency is between the operating point of light and full load. It is clear from the frequency curve that frequency is lowered to increase the Vo to compensate the reduced value with increase in load [5] [6].

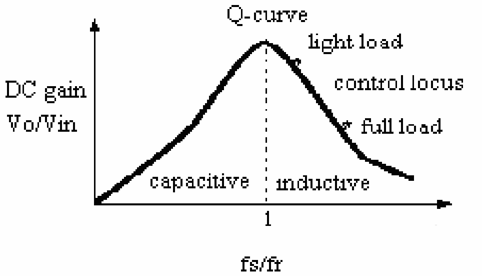

Fig.2. Frequency curve for SLR Converter

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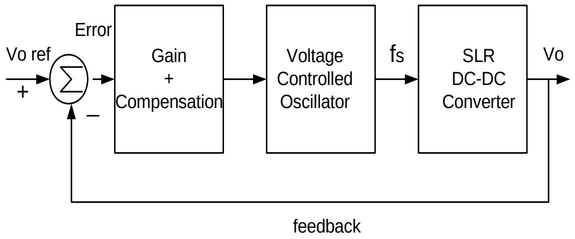

Fig.3. Control of SLR DC-DC converter

Fig 3 shows the basic block diagram of control scheme; the error between sensed output voltage and reference determines the output frequency fs of the voltage controlled oscillator (VCO), which in turn controls the switching of the two power switches (IGBTs). Thereby allowing the feedback circuit of SLR converter to respond to the level of the output voltage and convert it by corresponding change in the switching frequency to achieve the desired regulation level [7].

The open loop and close loop control methods to regulate the Vo are presented in the paper through simulation results. The practical implementation of the whole control scheme through DSP will be the next work in this area.

## II. OPEN- LOOP CONTROL OF SLR CONVERTER

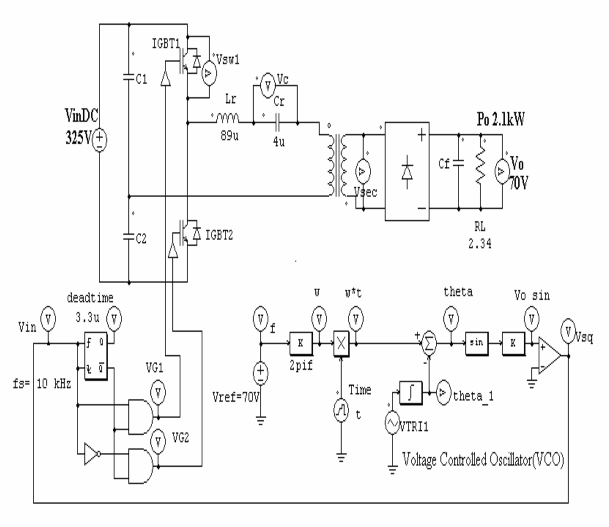

Fig.4. Simulation circuit for open loop control

The SLR converter is a frequency controlled converter. Fig 4 shows simulation circuit of 2.1 kW SLR converter. Here, the voltage controlled oscillator (VCO) is used to vary the switching frequency of the gating pulses. This is a voltage to frequency converter. The input voltage to the VCO is 70V. It is converted into frequency 2Пf (wr). Then it is multiplied with time reference and converted in to the phase of that frequency. The triangular reference is integrated to convert it into reference phase. The phase difference between input frequency and reference frequency is measured and converted into phase error in degree (ϴ). Which is further converted into the sinusoidal voltage through the sin block. The output of sin block is given to the comparator whose second input is grounded, so finally the sine wave is converted into the square wave pulses of magnitude 1.Thus phase difference between the frequencies is converted into the phase error, and then it is converted into the change in frequency [8] [9]. The output Vosin is given by;

$$Vosin = V_m \sin\theta$$

$$\theta = wt + \theta_1; \quad \theta_1 \text{ is adjusted by input}$$

Thus by changing the input voltage to VCO, output frequency of the VCO can be changed to regulate the Vo. The simulation is done by PSIM6 software for the total time of 0.03 sec. The simulation results for the open loop control scheme are presented from Fig 5 to Fig 9 for the different values of input voltages to the VCO.

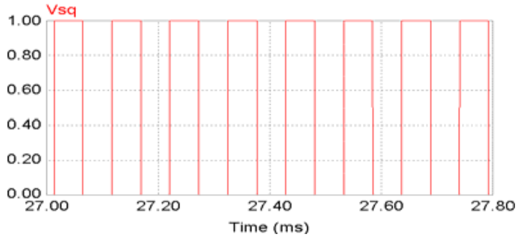

Fig.5. 10 kHz square wave pulses from VCO

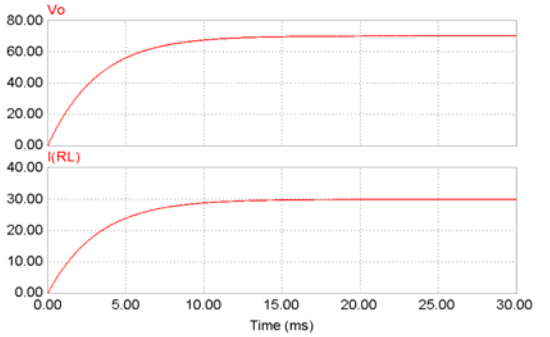

Fig.6. DC output voltage and current at VinVCO 70V and fs 10 kHz

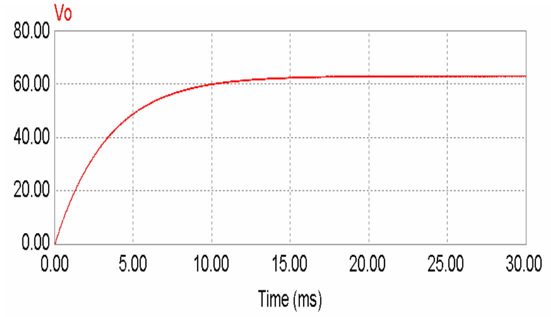

Fig.7. Vo DC at VinVCO 65V

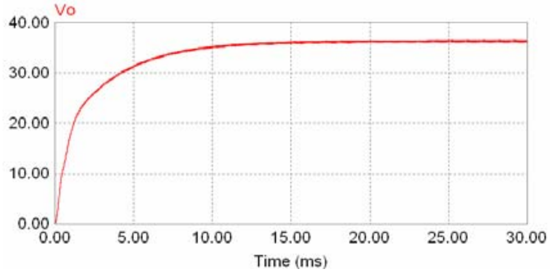

Fig.8. Vo DC at VinVCO 40V

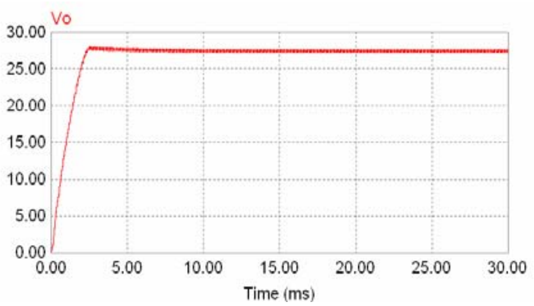

Fig.9. Vo DC at VinVCO 30V

Fig 5 shows 10 kHz square wave pulses from VCO at rated input of 70 V. The simulation results from Fig 6 to Fig 9 show that by changing the Vin to VCO from 70 V to 30 V, it is possible to regulate the output voltage from approximately 27 V to 70 V in open loop. As light load and no load regulation of SLR converter is poor due to limitation of frequency selectivity according to the frequency curve [10].

## III. CLOSE- LOOP CONTROL OF SLR CONVERTER

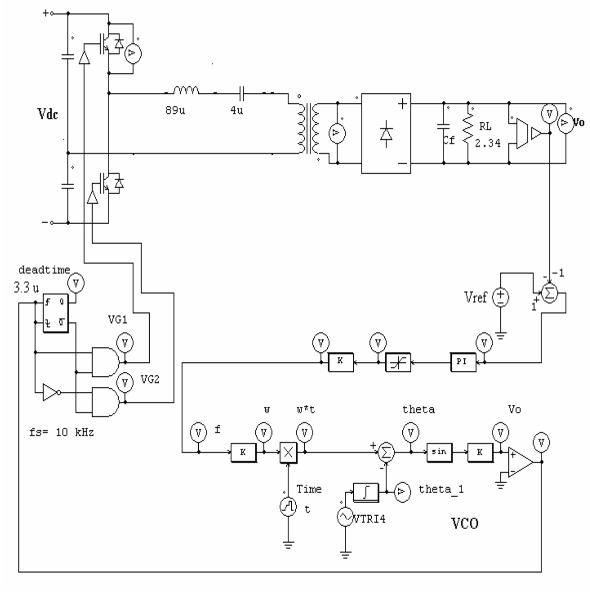

Fig.10. Simulation circuit for close loop control

The main target to close-loop control is to minimize switching losses of IGBTs. Fig 10 shows complete scheme of close loop variable frequency control of 2.1 kW SLR converter. A VCO can be realized in simulation. The circuit is simulated by PSIM6 software for the total time of 1.0 sec. In close loop variable frequency control of SLR converter the o/p DC voltage is sensed by a voltage sensor and given to the summer. The output of summer is the error between measured value and reference value of the output voltage. This error is given to the Proportional-Integral (PI) controller and then to the limiter. The PI controller used because it gives fast dynamic response to the errors caused by load change or external disturbance [11]. The summer, PI and limiter made a feedback loop in close loop system. Here the voltage mode control is used rather than current mode control because the voltage mode control gives fast response and easy to implement. In the proposed scheme the outer voltage feedback is taken. So it is possible to get high feedback gain and allows higher close-loop band width which results in reduction of output side filter component. In close-loop system if an error exceeds the predefined range and due to it if the output of PI exceeds the limiter range, the limiter clamped its output within prescribed limit. The output of PI controller is given to the voltage controlled oscillator (VCO) through a gain block K. The output of a VCO is square wave pulses which are finally given to the gate of both IGBTs through a dead time circuit. VCO is a voltage to frequency converter by which switching frequency is controlled in such a way that an error generated in output DC voltage is converted into the change of frequency to control the output voltage [12]. After tuning of gain and time constant of PI controller the output voltage is controlled in spite of line and load variations. Including this by changing the value of reference voltage (Vref) the output voltage of the converter can be regulated at the desired value [13] [14]. The controller design reduces output voltage ripple and provide fast response which are verified through simulation results presented.

The simulation results for the close loop system are given from Fig 11 to Fig 16. Fig 11 shows input and output of PI controller after tuning of its gain and time constant and input to the VCO at Vref equal to 1. Fig 12 shows output DC voltage and current at Vref 1. Fig 13 to 15 show input and output of PI and output DC voltage of the converter at references 0.8, 0.5 and 0.2 respectively. Thus the close loop scheme regulates the output voltage at desired value by changing the value of Vref.

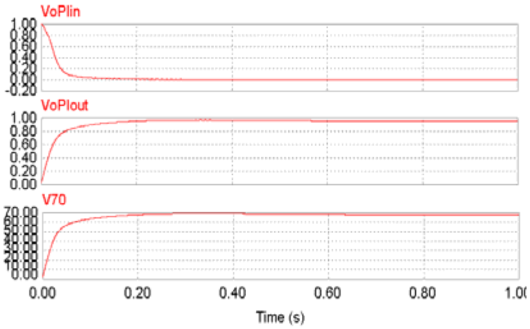

Fig.11. PI i/p, PI o/p and i/p to the VCO at Vref=1

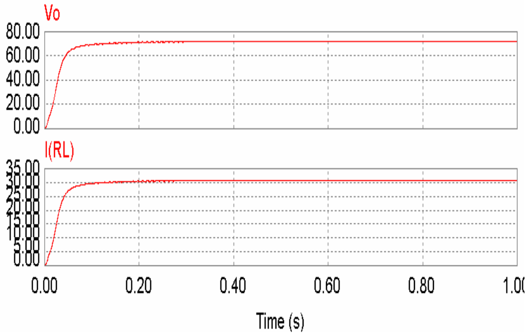

Fig.12. DC output voltage and current at Vref=1(Vo=70 V)

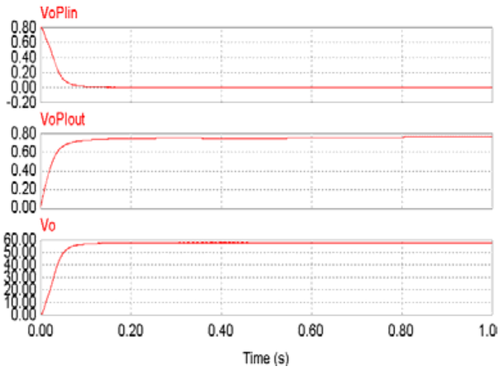

Fig. 13. PI i/p, PI o/p and Vo at Vref=0.8 (Vo=56 V)

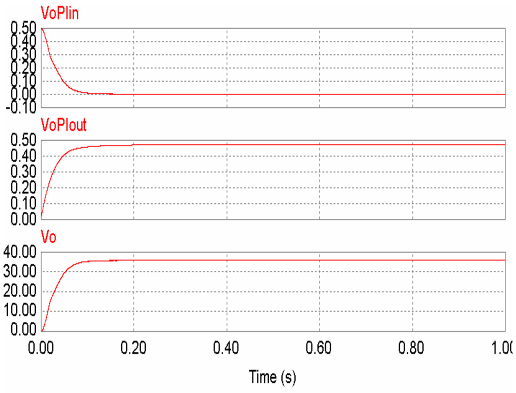

Fig. 13. PI i/p, PI o/p and Vo at Vref=0.5 (Vo=35 V)

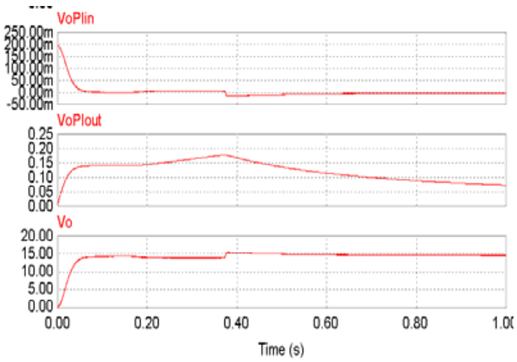

Fig.15. PI i/p, PI o/p and Vo at Vref=0.2 (Vo=14 V)

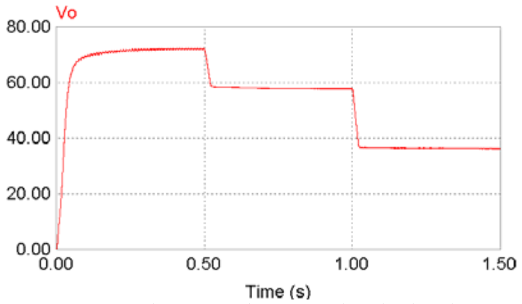

Fig.16. DC output voltage at Vref =1, 0.8 and 0.5 in close-loop system

Finally, Fig 16 shows the actual response of PI controller in close-loop variable frequency control scheme at different reference values in a particular simulation time. This shows that the close-loop system responds very well and regulates the DC output voltage in entire range from minimum to maximum value of reference voltage. Thus it is very clear from simulation results that controller provides nonlinear control over the wide range of operation [15] and overcome the draw back of conventional linear controller which gives reliable performance at one operating point only [16].

## IV CONCLUSION

In this paper new open-loop and close-loop variable frequency control methods of Series Loaded Resonant converter is proposed. Voltage Controlled Oscillator (VCO) is presented to get variable frequency in open-loop system and simulation results are given to regulate the output DC voltage in the control range of 27 V-70 V. The close loop system consists of PI controller including VCO which converts the error in output voltage to the change in switching frequency to control the output voltage. Regulation of output voltage has been achieved by changing the value of reference voltage to get the desired value of output voltage Vo in close-loop system. The simulation results at different references are presented to verify the control concept. It is also shown that theoretical predictions of variable frequency control match with the simulation results thus provided the accurate control of the SLR converter for wide range of operation .

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