REGULATED CAPACITOR CHARGING CIRCUIT USING A HIGH REACTANCE TRANSFORMER[1]

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Abstract

A high reactance transformer circuit is used to provide for the compact, simple, economic and reliable charging of a capacitor energy store to a predetermined and regulated voltage. The circuit can be operated from a single phase, three phase, or poly phase prime power source or service. The circuit employs a high-reactance transformer in combination with a phase-programmed switch. The transformer impedance limits the surge current loading on the prime power source. The phase-programmed switch is used to achieve the voltage regulation. The transformer secondary is rectified and is wound to provide the desired charge voltage on the capacitor store. The controller commands the primary switch that begins the charging cycle by closing at a predetermined phase relation to the prime power a.c. (alternating current) source. The predetermined phase is necessary to control the in-rush current to the primary of the transformer. The primary switch may be a fast solid state type such as an SCR (Silicon Controlled Rectifier). The same primary switch opens, or recovers in the open state at a current zero crossing, to remove the primary voltage when the capacitor store reaches full charge, and thus provides regulation of the charging voltage. The repetition rate of the charging circuit is limited to approximately 25% of the prime power a.c. source frequency for three phase applications and approximately 8% of the a.c. source frequency for single phase applications. The accuracy of the regulation also depends on the maximum repetition rate in relation to the source frequency.

I. BACKGROUND

Pulsed power applications are based upon storing a quantity of energy in a capacitor bank, which has been extracted from a prime power source, and then switching that energy out of the capacitor store on a faster time scale to achieve a higher peak power for a time duration which is shorter than the time required to initially charge the energy store. Circuits used to charge a capacitor store must have a current limiting feature because the capacitor at the beginning of the charging process is a short circuit and will therefore draw a current from the source limited only by the impedance or other similar characteristics of the charging circuit. In addition to the current surge limiting feature, the circuit must provide a feature which controls or regulates the maximum voltage to which the capacitor store is charged. This regulation feature must accommodate fluctuations in the prime power source and other parameters which may drift in time due to temperature variations or other factors.

The present state of the art approach for charging and regulating capacitive energy stores is the "switching regulator" type of power supply [1]. The principle of operation consists of directly rectifying the a.c. main power source to obtain a d.c. source. The direct rectification avoids the use of a large expensive transformer, only relatively small rectifiers are required. The d.c. thus obtained is then switched at a high frequency, typically 20 kHz or more, into a small capacitor through an inductor, and then into the primary of a high voltage step-up transformer. Solid state switching devices such as (Insulated Gate Bipolar Transistors) IGBT's or power (Monolithic Oxide Silicon Field Effect Transistors) MOSFET's are used. The high switching frequency permits the size of the transformer to be greatly reduced in relation to a transformer operating at the power line frequency, i.e. 20 kHz or higher compared to 60 Hz or 400 Hz. The secondary of the transformer connects through a high-voltage rectifier and then to the capacitive store. Each switching cycle of the circuit delivers a measured amount of energy to the capacitive store. The voltage on the capacitive store is sensed and compared to the desired full charge voltage. When that voltage is reached the switching is stopped, thus accomplishing the regulation function. In some variations of this type of switching regulator the frequency of the switching cycle is programmed in such a way as to maintain a more uniform power drain on the primary power line than would be obtained if the switching frequency were constant. Switching regulators work quite well but are complex and expensive. Since IGBTs and MOSFETs have limited power handling limitations, very large numbers of these components and associated circuits are required to handle high energy and/or high average power levels.

The purpose of this paper is to describe a simple, compact, efficient, and economic means for charging and regulating capacitor energy stores from single phase, three phase, or poly-phase prime power sources. The design, when used and applied within its fundamental

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14. ABSTRACT

A high reactance transformer circuit is used to provide for the compact, simple, economic and reliable charging of a capacitor energy store to a predetermined and regulated voltage. The circuit can be operated from a single phase, three phase, or poly phase prime power source or service. The circuit employs a high-reactance transformer in combination with a phase-programmed switch. The transformer impedance limits the surge current loading on the prime power source. The phaseprogrammed switch is used to achieve the voltage regulation. The transformer secondary is rectified and is wound to provide the desired charge voltage on the capacitor store. The controller commands the primary switch that begins the charging cycle by closing at a predetermined phase relation to the prime power a.c. (alternating current) source. The predetermined phase is necessary to control the in-rush current to the primary of the transformer. The primary switch may be a fast solid state type such as an SCR (Silicon Controlled Rectifier). The same primary switch opens, or recovers in the open state at a current zero crossing, to remove the primary voltage when the capacitor store reaches full charge, and thus provides regulation of the charging voltage. The repetition rate of the charging circuit is limited to approximately 25% of the prime power a.c. source frequency for three phase applications and approximately 8% of the a.c. source frequency for single phase applications. The accuracy of the regulation also depends on the maximum repetition rate in relation to the source frequency.

15. SUBJECT TERMS

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limitations, is superior in cost, reliability, and complexity to other known methods in use at the present time. It is also a purpose of the phase controlled a.c. switch portion of the design, to be used separately to limit the surge current, commonly a problem, when applying a.c. power to a transformer or other inductive load. When specifically applied to transformers, this portion of the design eliminates the transformer saturation problem which occurs as a result of applying a.c. power at a random voltage phase angle instead of at the optimum voltage phase angle defined by the design. The disadvantages of this design are poor power factor, high short circuit current, and the maximum repetition rate (ability to recharge the capacitive load after full discharge) is limited by the power line frequency (~8% of the line frequency for single phase and ~25% for three-phase).

II. DESIGN EXPLANATION

A basic block diagram for a single phase version of the circuit can be seen in Fig. 1. The major components are: the a.c. switch (such as a pair of SCRs, a triac, transistors, or any one of many other command triggered ON/OFF switches); a high impedance transformer which provides the voltage step-up or step-down and determines the maximum steady-state short circuit current that will load the power source; a rectifier assembly; and a control unit which accepts inputs from the load and user and provides properly phased control of the a.c. switches.

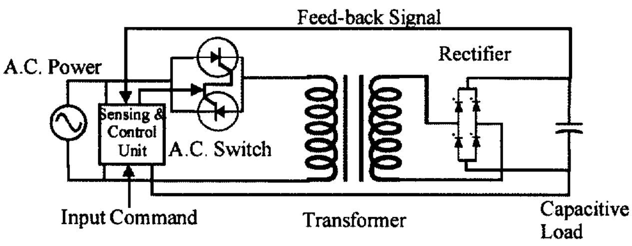
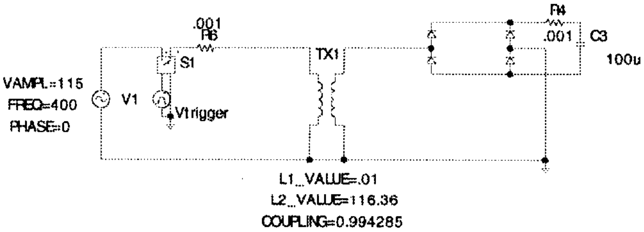


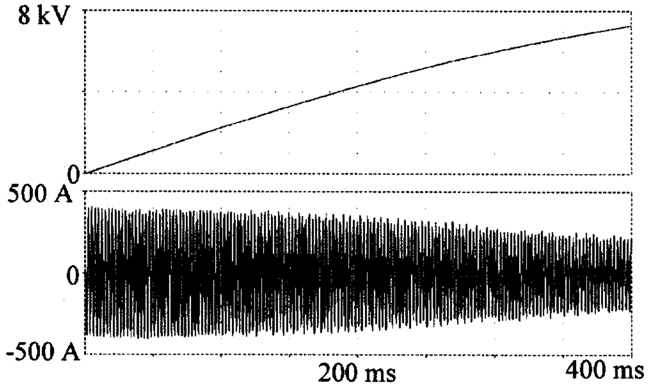
Fig. 1 Simplified Diagram of Charging Scheme

The single phase circuit works by first providing an input command to the control unit to begin the charging process. The input would also set the charge voltage for the capacitive load. Initially, the load is uncharged and presents a short circuit to the system. It is essential therefore to limit the short circuit current which would be required from the power source. The primary means for limiting this current in the steady-state regime is the leakage inductance of the transformer. However, there is also a transient surge current effect determined by the phase of the a.c. power source voltage in relation to the closing of the a.c. switch. It can be shown that if the switch closes when the phase of the of a.c. voltage is at its peak value (ϕ=90°), the transient surge is essentially eliminated (leaving only the steady-state surge current determined by the transformer). In the case of a three-phase source, there are three angles measured with respect to the source phase which must be maintained to eliminate the transient surge (ϕ=90°, 150°, and –90°). With this in mind, the switch is closed at the correct phase during each a.c. cycle and as time progresses, the capacitor voltage rises to the required final voltage value. When the controller senses that correct load voltage has been achieved, it stops triggering the a.c. switch which then opens at the next zero crossing, thus regulating the voltage on the load to the required value. Figure 2 is an example output for a circuit simulation showing the circuit diagram, the output voltage (voltage across the capacitive load), and the current through the prime power source. The design is based on the need to charge 5 kJ to 10 kV at 3 Hz with a 115 VAC, 400 Hz source. These specifications resulted in a design which limited the short circuit current to 400 A.

To implement this design, it is necessary to determine and/or evaluate the performance parameters, specifically the voltage-time characteristic and the RMS currents such that the transformer design parameters can be specified. The characterization of this type of design has been done by extensive circuit analysis and reduced to normalized curves (given in Figs. 3 – 6 for single and three phase designs). These curves provide the necessary information to design a single or three phase system, predict the performance parameters, and specify the ratings of the components. The design procedure is based on the characteristics of the equivalent circuit referred to the primary. The equivalent circuits for the single and three



A) Schematic



B) Top Trace: V(C3) = V output
Bottom Trace: I(V1) = I source

Fig. 2 Example Simulation

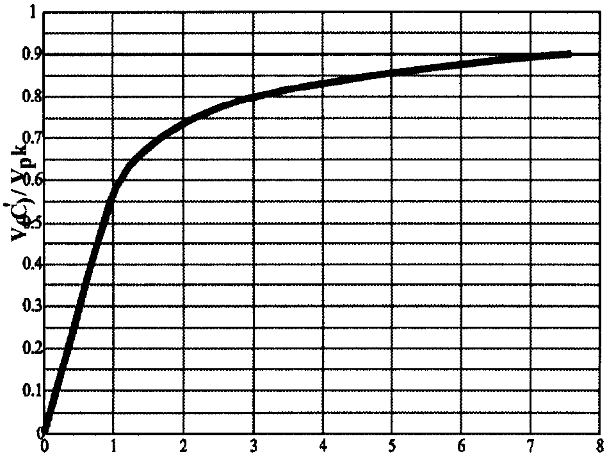


Fig. 3 Single Phase -
Normalized Voltage vs Normalized Time

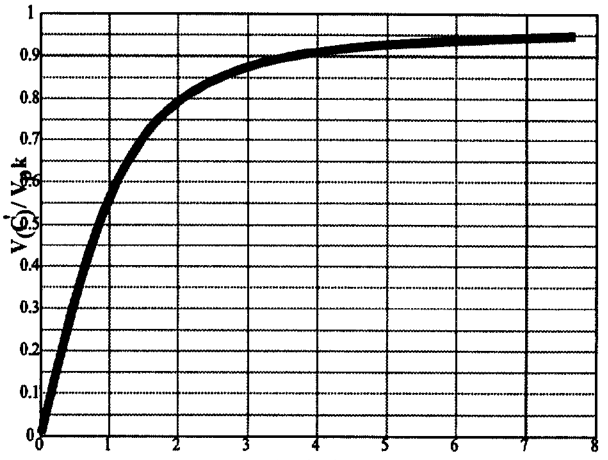


Fig. 5 Three Phase -
Normalized Voltage vs Normalized Time

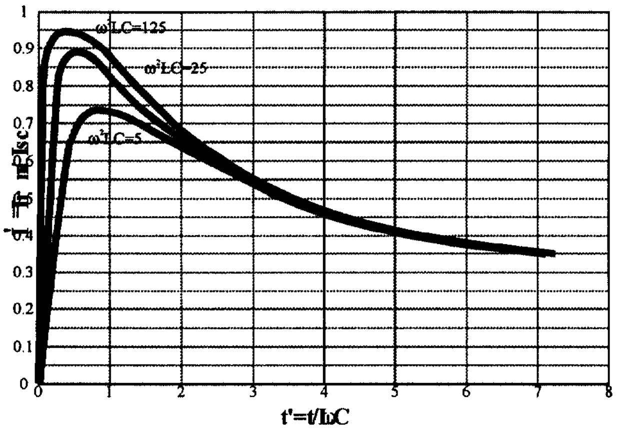


Fig. 4 Single Phase -
Normalized RMS Line Current vs Normalized Time

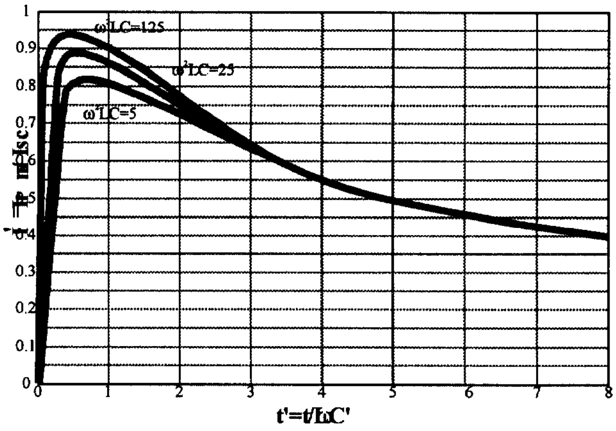


Fig. 6 Three Phase -
Normalized RMS Line Current vs Normalized Time

phase cases are shown in Fig. 7 and Fig. 8 respectively. The inductance L is the equivalent leakage of the circuit referred to the primary line. This inductance includes that of the transformer plus any external circuit inductance that may be present or added for trimming purposes. The value of C' is the equivalent capacitance referred to the primary. It is determined using the voltage to which it is charged, referred to the primary, and the total stored energy requirement. The RMS and short circuit current specifications for the transformer are determined from the equivalent primary circuit. The last step is to determine the transformer voltage ratio to provide the required output on the actual load capacitor C.

III. DESIGN EXAMPLE

An example application is to charge a capacitor to 100 kJ every 2.5 seconds from a 480 volt three phase power line. The design procedure is iterative and requires an initial estimate for t and t'. A good first estimate is t= t'=2.5. From Fig. 5, with t'=2.5 the normalized voltage is 0.85. The peak voltage is 480*1.414=679 V. The voltage on C' corresponding to 100,000 Joules is therefore, 679*0.85= 577 V. This determines the value of C' as 0.6 F. Since t'=t/ωLC' then the value of L is determined as 4.42 mH. The short circuit current is 80/(0.00442*377*1.732)=166 A. From Fig. 6 the ratio of RMS current to short circuit current is 0.7, so the RMS line current is 0.7*166=116 A. The kVA is 480*116*1.732=96.6 kVA which gives a power factor of

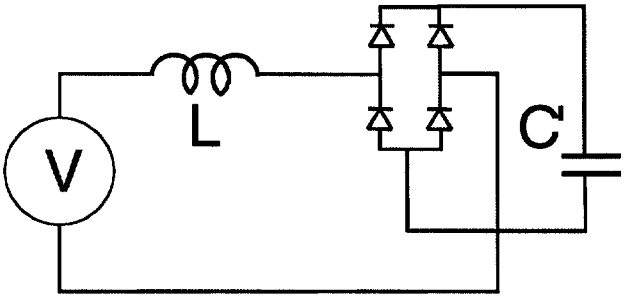


Fig. 7 Single Phase Equivalent Circuit

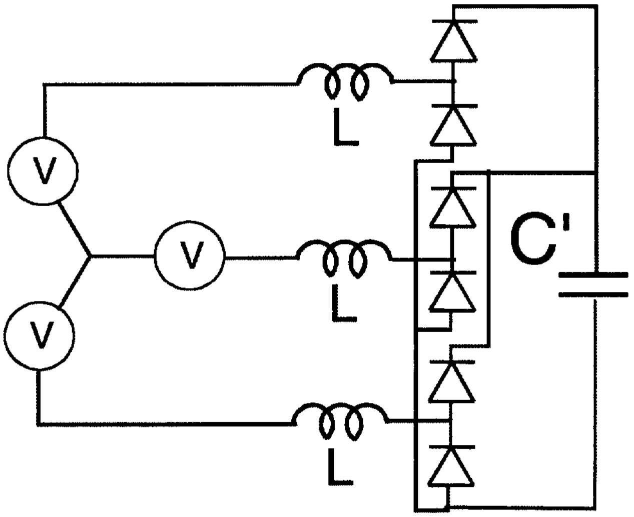


Fig. 8 Three Phase Equivalent Circuit

41.4%. Thus far we have used the equivalent capacitance C' which is referred to the primary or line side of the transformer. If the actual load capacitor is to be charged to 100kV then the peak secondary transformer voltage will be 100 kV divided by 0.85 (from Fig. 5) or 118 kV peak or 83 kV RMS. The final transformer specification is, primary 480 V at 201 A, secondary 83 kV at 0.67 A, primary short circuit current 166 A, all values being line to line voltages and line currents. From these values, the ratings for all the components (a.c. switches, rectifier stacks, and the main transformer) can be determined.

IV. CONCLUSIONS

This paper has presented a circuit design which will charge capacitive loads from single or multi-phase a.c. power. Four major advantages and/or new features of this circuit design are: (1) the use of the passive characteristics of a high impedance transformer to limit the surge current associated with the charging of a capacitive energy store from a voltage source, rather than a large number of complex active components as in the switching type power supply; (2) the further reduction and control of the surge current, by a factor of approximately two, by the use of the optimum phase angle controlled switching; (3) the use of the a.c. switch to accomplish the regulation of the capacitive energy store by sensing the store voltage and opening the a.c. switch to interrupt the charging when the desired or regulated voltage level is reached and (4) this design (unlike designs based on switching power supplies [2]) can be overloaded up to adiabatic limit on the transformer as long as care is taken with rating the switches. Note that the switches in this design are SCR type switches which can have very high current ratings as compared to the transistor style switches in most switching power supplies which have a much lower current rating.

V. REFERENCES

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[2] J. P. O'Loughlin, S. E. Calico, and D. L. Loree, "Optimization of Adiabatic Inverter Transformers," in Conference Record of the 22nd International Power Modulator Symposium, Boca Raton, FL, 25-27 June 1996, pp. 218-221.