LOW COST THREE-PHASE EMERGENCY POWER SUPPLY

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Abstract- This paper demonstrates the analysis and the implementation of a three-phase supply to be used as an emergency power source, particularly for domestic and commercial applications. The system has been constructed in a modular form for easier maintenance; including a battery bank, an electronic battery charger, a DC chopper, a 3-ph multi-stepped inverter, an optional 3-ph low pass filter, an automatic transfer switch (ATS), a low power switched mode supply and a control unit generating the required gate signals. Such configuration validates the use of low-voltage low-frequency low-cost BJT transistors and transformers, hence reducing the overall cost. The ATS provides an off-line system operation to reduce its running cost and increase its lifetime. The overall system has been tested up to a 3-ph load of 9kW - 380V - 50Hz. Simulated results are matched with the corresponding practical results, showing the effectiveness of the system with higher efficiency, lower voltage regulation and more safe operation comparing to the conventional emergency electro-mechanical alternator.

Keywords- Power supply, chopper, muti-stepped inverter, ATS, UPS, simulation and implementation.

I. NOMENCLATURE

- $E_{ch}$,$I_B$ & $R_{LB}$ Battery voltage, charging current and limiting resistance
- $f_c$ & $V_{sm}$ The AC supply frequency and maximum voltage
- $V_{DC}$,$N_P$&$N_S$ Switched mode power supply voltage, transformer primary and secondary number of turns
- $n$ Counter 1, 2, ------ n
- $T_{on}$,$T_{off}$ Chopper switching time period, on-time and off-time
- $V_{ch}(on)$ & $I_{ch}(on)$ Chopper voltage and current during the on-time
- $V_{ch}(off)$ & $I_{ch}(off)$ Chopper voltage and current during the off-time
- $G_s$, $L_s$ & $C_f$ Filter transfer function, inductance and capacitance
- $s$ Laplace operator
- $V_{BE}$ Transistor base-emitter voltage

II. INTRODUCTION

Nowadays, power supplies are extensively used in many field of applications, including laboratories, domestic, commercial and industrial applications. Different configurations of the uninterruptible power supplies (UPS), commonly used as standby sources for critical loads, have been discussed in [1]-[4]. The pulse width modulation technique (PWM) is utilized in the UPS, particularly for low voltage, and requires high frequency devices [5]-[8]. Matrix converters have been received many research interests [9] to directly produce a controlled AC voltage, but still not closer enough to industrial applications. Resonant inverters [10] are also utilized in power supplies with low harmonic distortions but with additional cost and lower efficiency due to the LC resonant filter in the output stage. Recently, multilevel inverters have been extensively researched and introduced for industrial applications, such as high voltage utilities and electrical machine drives [11]-[14]. They have the merits of higher-voltage, higher-power, lower-frequency and lower-harmonic distortion capabilities. In this paper, a three-phase emergency power supply, based on multi-stepped inverters, is introduced. The system is theoretically analyzed and practically implemented. The effectiveness of the setup is demonstrated through both simulated and practical results.

III. SYSTEM OPERATION

Figure 1 shows the overall block diagram of the proposed 3-ph static emergency power supply in a modular form. System operation can be divided into two modes as follows:-

A. OFF-MODE: When the main supply is on, the 3-ph load is fed from this main supply through the automatic transfer switch unit (ATS). The electronic battery charger charges the battery bank, keeping its voltage level constant. The switched mode power supply is disconnected from the battery by the normally closed main supply contactor ($K_M$). The power to the inverter is also off by the normally opened contactor of the battery bus ($K_B$). Both contactors ($K_M$ & $K_B$) are in the ATS unit. None of the gate signals is then generated, and both the chopper and the inverter are completely off. Hence through this mode of operation, the emergency power supply unit is completely shut down, saving the overall power and increasing the unit lifetime.

B. ON-MODE: In case of the main supply failure, the contactor $K_B$ is activated while $K_M$ is deactivated. Thus, the switched mode power supply is turned on and the gate signals are generated. The chopper unit converts the constant DC battery voltage to a controlled DC output voltage feeding the 3-ph inverter. This multi-stepped inverter produces a 3-ph AC voltage to feed the 3-ph load through the ATS unit. The charger unit is now off and the battery bank will continuously feed the system according to its ampere-hour capacity. If the main supply is back, the ATS unit will bring the system back to the off-mode. The standby switch ($S_B$) is turned off only in case of the unit maintenance operation.

IV. ANALYSIS OF SYSTEM COMPONENTS

A. Battery Bank

The battery bank is utilized as an energy reservoir during the normal off-mode operation, while it becomes the source of the energy during the on-mode. It consists of eight 12V, 300 A/H sealed batteries connected in series to provide a total DC voltage of 96V.

B. Battery Charger

The battery charger unit converts the main AC voltage to a regulated DC voltage through a transformer, an H-bridge diode rectifier and a linear power regulator. The average charging current can be given as:-

$$I_B = \frac{1}{\pi} \int_{\sin^{-1}}^{\pi} \frac{E_B}{V_{sm}} \sin(2\pi f t - E_B) \cdot \frac{R_{LB}}{V_{sm}}$$

(1)
Simulated waveforms of the battery voltage and charging current are shown in figure 2.

C- Switched Mode Power Supply

The switched mode power supply can be considered as a DC-to-DC transformer. It efficiently converts the DC battery voltage to different isolated DC voltages, feeding the chopper and inverter gate drive circuits. Circuit diagram and waveforms of such power supply are depicted in figure 3. The DC output voltage can be generally written as:

$$V_{DCn} = E_B \frac{N_p}{N_{sn}}$$

Hence different DC voltages ($V_{DCn}$) can be obtained using different transformers with different secondary windings ($N_{sn}$).

D- The ATS

The automatic transfer switch (ATS) controls the power flow to the load through the different operation modes. It has three different power contactors: the main contactor ($K_{M}$), the emergency supply contactor ($K_{E}$) and the battery contactor ($K_{B}$).
(K_M). The operation sequence is illustrated through the timing diagram shown in figure 4.

**E- The Chopper**

The Chopper is utilized to convert the fixed DC battery voltage to a regulated DC voltage, feeding the 3-ph inverter, hence regulating the final AC 3-ph output load voltage. Series inductor (L_ch) and shunt capacitor (C_ch) are provided in the chopper circuit to stabilize and reduce voltage ripple in the chopper dc output voltage. The chopper output voltage, which is the voltage of the shunt capacitor, during both ON and OFF periods, can be written as:

\[
V_{ch(on)} = \frac{1}{C_{ch}} \int_{0}^{T_{on}} i_{on} \, dt = E_B - L_{ch} \frac{d}{dt}i_{on}
\]  

(3)

\[
V_{ch(off)} = \frac{1}{C_{ch}} \int_{T_{on}}^{T_{off}} i_{off} \, dt = 0 - L_{ch} \frac{d}{dt}i_{off}
\]  

(4)

\[\text{Figure 4. The ATS sequence of operation}\]

\[\text{Figure 5. Simulated chopper circuit diagram using Simulink program}\]

\[\text{Figure 6. Effect of varying the duty cycle on the chopper waveforms for a constant load}\]

\[\text{Figure 7. Varying the duty cycle to keep the chopper output dc voltage constant for different load conditions}\]
For $E_d=96V$, $L_{ch}=150\,\text{mH}$, $C_{ch}=400\,\mu\text{F}$ and $T_{ch}=1/200\,\text{sec}$, the chopper voltage ($V_{ch}$) is regulated by the control unit through the adjustment of the on-time value ($T_{on}$). The circuit diagram, gate signals and the output voltage waveforms of the simulated chopper for different operation conditions are shown in figures 6 and 7. It should be noted that the chopper is designed as two identical circuits (see figure 5). Each has a transistor, a freewheeling diode and an inductor, and delivers power through half of the chopper cycle. This configuration reduces stresses on the switching devices and ripples level in the final output dc voltage.

**F- The 3-ph Multi-stepped Inverter**

The stepped sine wave can be generated by the summation of different square waves with different magnitudes and phase shifts. The analysis and implementation of a 1-ph, 50Hz, five-steps inverter have been introduced by the authors in [15]. The 3-ph inverter, proposed in this paper, consists of three identical 1-ph, 50Hz, five-steps, sine-wave inverters, each shifted by $120^\circ$ in the gate signals. This 3-ph inverter converts the regulated DC voltage received from the chopper into a 3-ph multi-stepped sine wave output voltage to feed the load through the contactor $K_E$ in the ATS unit. Inverter circuit diagram is shown in figure 8 and simulated 3-ph output voltage of such inverter, star-connected, are depicted in figure 9. Such inverter configuration required low voltage low frequency switching devices, hence reducing the overall cost.

**G. Control and generation of gate signals**

A sequential circuit is designed to provide the 3-ph stepped inverter with 30 gate signals of 50Hz frequency and shifted by $12^\circ$ (each phase has 5 inverters with 2 transistors per each, i.e. $3*5*2=30$). Another circuit is designed to

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*Figure 8. Circuit diagram of the 3-ph 5-stepped inverter*

*Figure 9. Simulated output voltage waveforms of the 3-ph 5-stepped inverter*
provide the DC chopper with the required 200Hz gate signals, while the duty cycle is adapted through an analog closed loop proportional plus integral (PI) control unit, according to the difference between the required and actual feedback of the output load voltage. All gate drive circuits are designed to have a source of isolation and amplification in order to provide the suitable voltage and current levels for the power switching devices.

H- Output Filter
An optional 3-ph LC low pass filter may be used to reduce the total harmonic distortion (THD) of the final output load voltage from 12% to 5%. The per-phase transfer function of such filter may be given as:

$$G_f = \frac{1 / L_f C_f}{s^2 + (1 / L_f C_f)} \quad (5)$$

Simulation waveforms of output load voltage are shown in figure 10 with and without such LC filter (for $L_f = 3\text{mH}$ and $C_f = 100\mu F$).

V. PRACTICAL IMPLEMENTATION
The overall setup shown in figure 1 has been designed and practically implemented for a full load operation of 9kW, 380V, and 50Hz. The System is built in a modular form and each module has been individually tested for different operating conditions. The modules have been connected together and the overall system has been tested. The actual waveforms have been obtained using digital scope then plotted using Matlab program. Figure 11 shows the practical battery voltage and charging current during the off-mode system operation. It can be seen that these actual waveforms correlate with simulated waveforms shown in figure 2. Figure 12 depicts the 3-ph line and phase voltage waveforms of the implemented system, which are similar to the corresponding simulated results obtained in figure 10. Practical waveforms of the AC load voltage, DC chopper output voltage, gate signal and transistor current (represented by $V_{BE}$) are illustrated in figure 13 for different load values. It can be noticed that chopper gate signal, currents and voltage are continuously controlled and varied in order to regulate and keep the AC load voltage constant (in shape and magnitude) regardless the variation of load values. The simulation results obtained in figure 7 are matched with the practical results in figure 13. Figure 14.a shows the actual load voltage fed from the main supply during the off-mode of operation, while figure 14.b shows the same waveforms during the on-mode and the load is fed from the proposed emergency supply. It can be seen that voltage of the emergency supply is approximately typical to the main supply voltage. At the full load condition, system efficiency is found to be around 90%, voltage regulation is about 3% and the total harmonic distortion (with the LC filter) is less than 5%. The continuous operation time of the system is determined according to the Ampere-hour capacity of the battery bank. These practical results show the effectiveness of the proposed setup and validate such system for applications as an emergency supply with higher efficiency, lower operation requirements and more safe operation comparing to the conventional alternator.
VI. CONCLUSIONS
A configuration of an AC 3-ph emergency static power supply, based on battery charger, DC chopper, 3-ph multi-stepped inverter and ATS has been demonstrated. The proposed setup validates the use of low cost switching devices and increases the unit lifetime. The overall system has been implemented and tested up to a 3-ph load of 9kW - 380V - 50Hz. Different simulated and practical results have been obtained for the proposed system, showing the effectiveness of the system with high efficiency, low voltage regulation, low harmonic distortion and safe operation. The system can be used as an emergency supply for domestic and commercial applications.

VII. REFERENCES

Figure 13. Practical waveforms for different 3-ph loads (no-load, 1kW, 4.5kW and 9kW)

Figure 14. Oscilloscope graph for the actual load voltage