

A MULTI-PHASE OFFLINE POWER SUPPLY FOR BATTLEFIELD POWER

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Abstract— A matrix converter and variable-speed diesel generator are integrated to create a three-phase utility power supply. The matrix converter is designed to meet tight harmonic and transient response requirements while allowing variable voltage and frequency input from the generator's permanent magnet alternator. This enables the generator to provide stable power over a range of engine speeds and load conditions. Test results for the 10 kW offline power supply are provided to demonstrate system performance.

I. INTRODUCTION

Generator systems that provide flexible AC power are rapidly becoming necessary for battlefield applications. This is due to the requirements for fuel efficiency, electrical flexibility, and reliability. A variable speed generator that allows operation over a wide engine RPM without compromising AC output power quality improves engine efficiency at light load and reduces soot buildup in the exhaust stream, a primary failure mode for diesel generators. State-of-the-art commercial products exist in the 7.5 kW power level using a permanent magnet (PM) alternator and single-phase voltage source inverter (VSI). This technique was extended to three-phase designs also based on the VSI [1],[2].

The use of the variable speed generator and matrix converter as a utility power source is presented for a 10kW demonstration unit built by the US Army Research Laboratory and the University of Nottingham, UK. This research collaboration created a 10kW matrix converter designed to deliver 12.6 kVA at 208VAC line-line with frequency range of 50 Hz to 400Hz.

The block diagram in Fig. 1 shows the assembly of the engine/generator/matrix converter to enable variable speed operation. A three-cylinder turbocharged diesel engine is coupled directly to a permanent magnet (PM) alternator. The diesel engine has a 22kW peak output at sea level. The electrical output voltage within the allowed engine RPM ranges from 260 to 480VAC line-line with a frequency of up to 700 Hz.

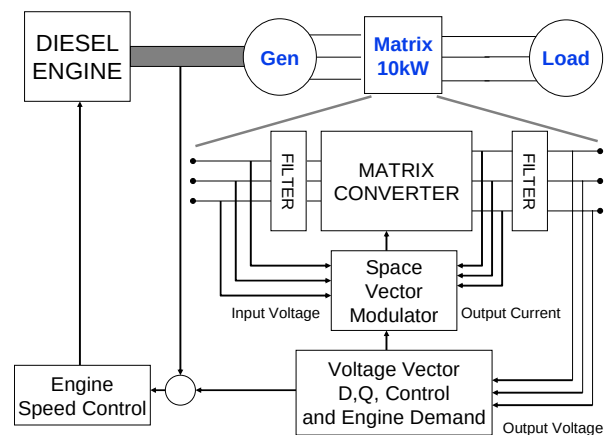


Fig. 1. Engine/generator system overview.

This generator prototype will be demonstrated as a voltage controlled power source for a balanced three-phase load. Test results of the power converter will include voltage regulation under various loads, load step response, and harmonic performance.

II. MATRIX CONVERTER POWER STAGE

The justification for using the matrix converter is based on its all-silicon power conversion capability. The removal of electrolytic capacitors allows for extreme environment storage and wider operating temperature range than with electrolytic capacitors. Energy storage traditionally provided by the DC link in the VSI is instead drawn from the engine-generator rotor inertia. The matrix converter also draws sinusoidal input currents at any power factor, making it useful for frequency changer applications when grid power is available as an alternative to portable engine power. Matrix conversion is also capable of higher efficiency operation at the high switching frequencies required for this application. Literature shows that at high switching frequencies (greater than 8 kHz) switching and conduction losses in the matrix converter are lower than those of a similarly rated back to back VSI [3]-[4].

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A drawback to the matrix converter is the theoretical voltage conversion limit of 0.86. This limit is due to the fact that the maximum output voltage can never be higher than the greatest difference between the line-to-line voltages of the three phase input line.

The matrix converter presented uses the traditional nine bi-directional semiconductor switch topology, (18 total common-emitter-connected IGBTs). This is compared to the 12 switches needed for a typical back-to-back VSI. The voltage stress for the IGBTs used in the matrix converter is one and a half times the peak amplitude of the input voltage. This value is about 900V accounting for switching overshoot at maximum generator RPM. A traditional VSI would have similar voltage stress. Therefore 1200V IGBTs are used along with 1.5μF snubber capacitors across the three-phase input lines. Current stress is the same as that encountered in the traditional VSI but average device current is one third the rated output current because the average duty cycle of each switch is one-third that of the switches in a VSI. Device current ratings are 40A for a 208V/12.6kVA three-phase supply.

Losses in the matrix converter bridge depend on both the collector-emitter saturation voltage drop of the IGBT and the forward voltage drop of a diode used to block reverse conduction of the IGBT. Once linearized, the conduction voltage drop as a function of current for the IGBT and diode is:

$$V_{CE(SAT)} = V_{CE0} + V_{F0} + r_{CE} \cdot I_C + r_D \cdot I_C \quad (1)$$

Where V_{CE0} and V_{F0} is the forward voltage drop at zero current for the IGBT and diode and r_{CE} and r_D is the linearized on-state resistance of the IGBT and diode respectively.

Now the conduction loss for each phase of the matrix converter can then be calculated by:

$$P_{COND,PHASE} = (V_{CE0} + V_{F0}) \cdot I_0 \cdot \left(\frac{2\sqrt{2}}{\pi} \right) + (r_{CE} + r_D) \cdot I_0^2 \quad (2)$$

Overall power loss as a function of switching frequency is then calculated in comparison with other power conversion strategies as shown in Fig. 2. Given our switching frequency of 25kHz, this translates to reduced switching losses over the VSI [7].

An overlapping switch commutation technique is used in this matrix converter to assure that the input lines are never short-circuited and that the output lines are never open-circuited. This method has the additional benefit of zero current switching of the IGBTs if the outgoing device is reverse biased by the turn-on of the incoming device. Since this may occur 50% of the time, it is better to describe the technique as semi-soft current commutation [5].

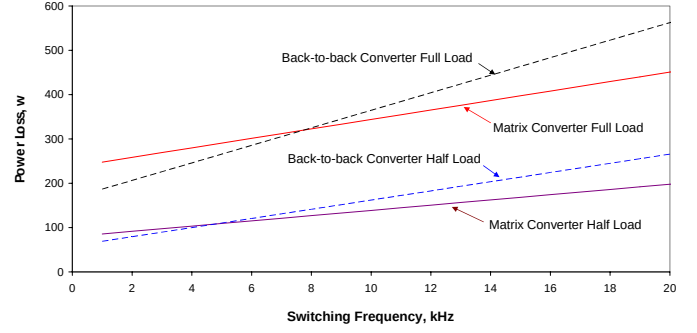


Fig. 2. Power loss as a function of switching frequency in various converters

Overshoot due to load shedding or device failure is limited by the use of a transient voltage clamp shown in Fig. 3. This clamp protects the power stage by rectifying both the input and output AC line. The circuit then stores the energy from voltage spikes generated if the source and load commutations are corrupted by failed switches. The energy stored in the capacitor is automatically bled off into a resistive brake circuit in case continued spikes from a failed switch force charge into this circuit.

III. MODULATION DESIGN

Modulation of this matrix converter is based on the scheme developed in [6]. This scheme uses a space vector modulation strategy that controls both the input and output voltage by selecting appropriate switch combinations that simultaneously meet the requirements of both the output voltage and input current to the matrix converter:

1. The input terminals must never short-circuit.
2. The output load must never open-circuit.

There are 27 of these switch vectors, however only 18 are necessary to meet the above criteria, in addition to three zero-vectors.

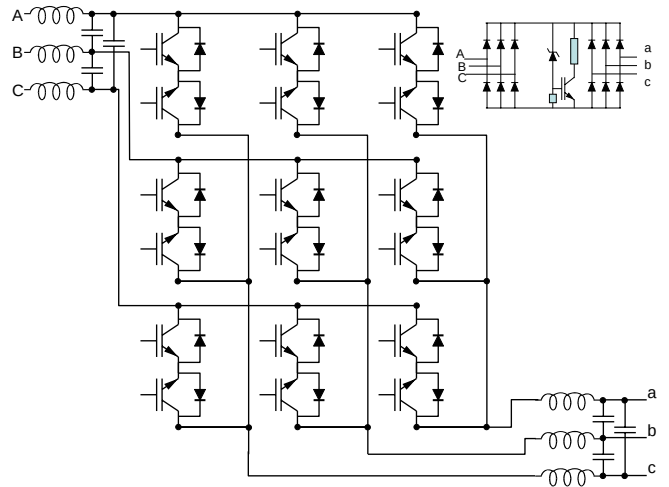


Fig. 3. Matrix converter schematic including diode-bridge active clamp (upper right corner).

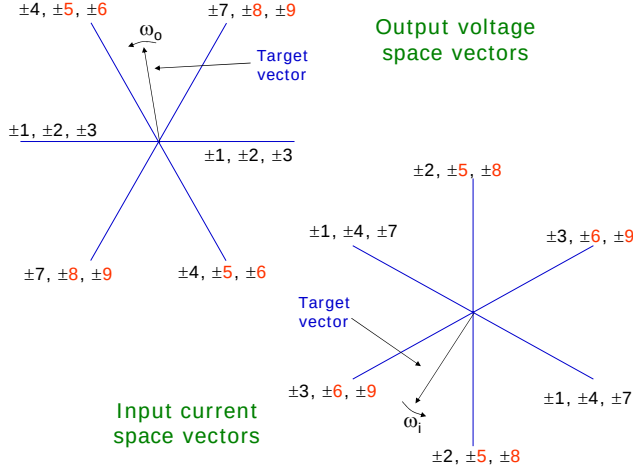


Fig. 4. Modulation algorithm constraint on target vector synthesis

To create the desired voltage and frequency at the output, a target vector representing output voltage amplitude is commanded to rotate at a desired frequency. An identification of the sector containing the commanded voltage vector is done so that the space vector modulator chooses the appropriate switching vectors. The additional task for the matrix converter is to also control the input current vector simultaneously. Fig. 4 shows that four vectors (5, 6, 8, and 9) are common to the vector location of both the input current vector and output voltage vector. These vectors are therefore the only ones used while the desired vector is in a particular sector.

The modulator, using these target vectors places them in order below with the three zero-vectors included in each cycle. The following table shows the example sequence of two sets of the six total switching vectors sent in a sampling period based on the vector locations of Fig. 4. This includes three zero vectors labeled by "O".

O ₁	V ₁	V ₂	O ₂	V ₃	V ₄	O ₃	V ₄	V ₃	O ₂	V ₂	V ₁	O ₁
19	5	6	20	8	9	21	9	8	20	6	5	19

The voltage/current sampling positions are shown by the lines under the shaded zero vectors. It is here that the processor recalculates the subsequent vectors. Each sequence of vectors and their duty cycles are decided upon by the DSP and sent to the FPGA to be executed during the next a 40μs period. The resulting speed at which the vectors are delivered yields an effective switching frequency of 16 kHz. This is found by dividing the number of switching vectors per cycle (six in this modulation technique), by the number of bidirectional switches in the power stage (9), and finally multiplying by the sampling frequency (25 kHz).

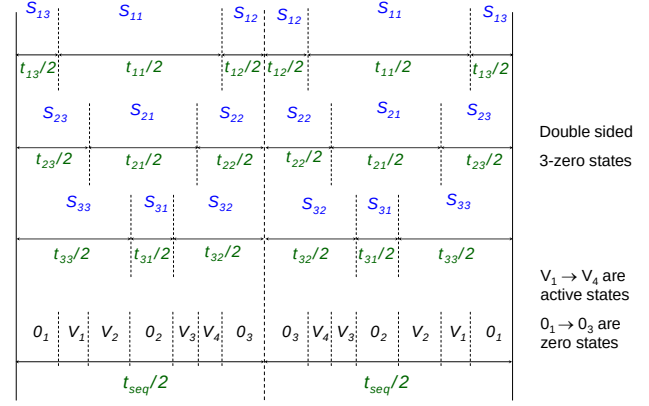


Fig. 5. Vector sequences for double-sided three zero-state switching method.

The choice of switching vectors takes advantage of a symmetrical pattern in which the last vector in the set of three switching patterns becomes the first in the next period. The effect of this pattern yields a 33% reduction in switching losses. Coupled with the semi-soft commutation, the resulting gains in efficiency offset such losses as those created by having current direction sensor diodes in series with the output [7].

IV. OUTPUT VOLTAGE CONTROL

The development of a power conversion system for supplying utility power requires tight output voltage regulation and low total harmonic distortion (THD). This system was therefore designed to operate at a high switching frequency to meet these specifications and permit the smallest possible output filter design. The target THD was chosen to be 3% with an eventual goal of meeting a 1% requirement.

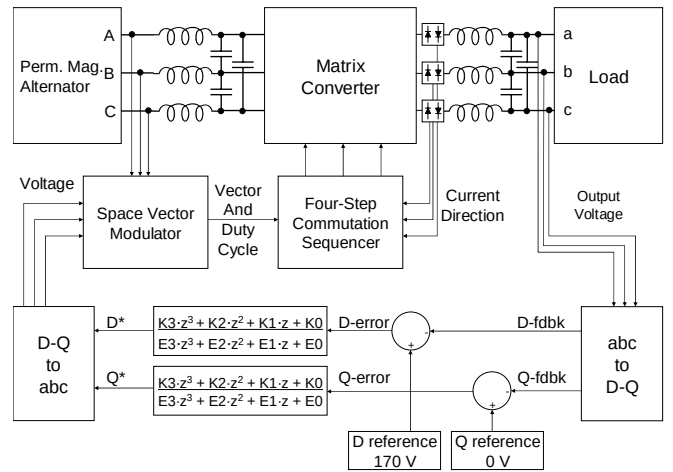


Fig. 6. D-Q controller for output voltage regulation of matrix converter.

A single loop digital controller operating in the d-q frame is used to close the output voltage loop as shown in the control block diagram of Fig. 6. An optimization program was employed to yield the appropriate compensator type and coefficients. In this program were modeled antialiasing filters, sampling delay, and modulation sampling delay. Traditional root-locus methods using linearized models of the power converters were abandoned due to the complex nonlinearities of the output filters, powerstage, and modulation scheme. Instead a Matlab® genetic algorithm (GA) toolkit was created to automatically tune the controller parameters in the discrete z-domain. The GA uses principles of evolution, natural selection, and genetics to yield an optimization technique for this problem.

The software first defines the order and structure of the controller and then searches for the optimum value of its parameters. The structure of the controller can include a gain, a pure integrator, a proportional-integral (PI) regulator, real poles and zeros, and complex poles and zeros. The user can then set bounds for the controller parameters, probability of mutation, and crossover. The software begins a recursive search for these parameters using a simulation of the whole system and then using the results to evaluate the fitness based on the original specification, in our case, total harmonic distortion.

It is important to note that genetic algorithms can get stuck just like other optimization techniques, but the use of mutations and crossovers help it to avoid local optimum and cover a wide search space, including results that may be totally bogus, like negative PID controller gains.

The strict performance requirements on both transient overshoot and THD make the controller design particularly difficult. The resonant output filter, which at no-load has no damping, causes overshoot when the load is shed. Also steady state control is affected by the modulation strategy of the matrix converter. The GA technique therefore tries to find the best compromise between quick response to transients and accurate steady-state voltage regulation [8].

Various tests of loading and unloading the matrix converter were carried out to show the capability of the controller to respond to step load changes. The illustration used in this example is demonstrated on the space vector modulated matrix converter running the fifth order compensator depicted in Fig. 6. The d-q axis test results are shown to best illustrate the response of the compensator. In the step load test shown in Fig. 7 the output line-line voltage of the matrix converter is 100VAC and the input is 200VAC, the load step is from full rated current to zero current.

The controller shows both its strengths and weaknesses in Fig. 7. Note the large amount of noise in frames A,B. This noise is brought about by a high bandwidth (2.3 kHz) capable controller that over-compensates for small dc error.

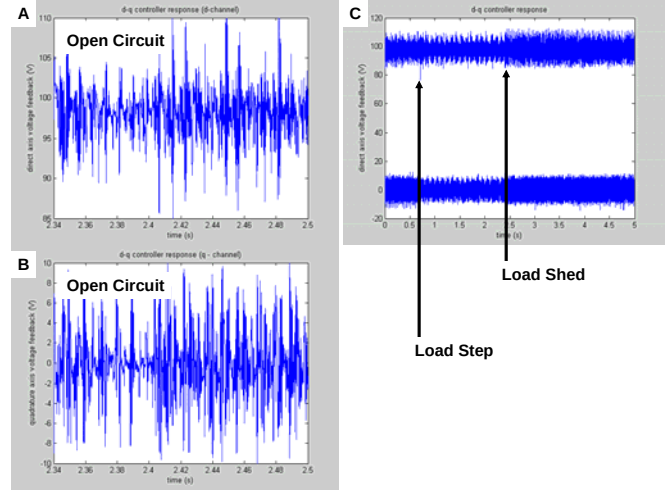


Fig. 7. Controller performance to steady-state and load step situations, Open Circuit (A.,B.), and load step/shed (C.).

However this same controller also responds flawlessly to a load shed/load step event as shown in frame C. Full load step/shed shows almost no evidence of transient overshoot, only system damping while the load is in place delineates the existence of load on the system.

VI. PERFORMANCE

The operation of the matrix converter was tested against inductive and resistive loads at power steps from 0%, 50%, and 100%. A THD analysis was also done to determine the load dependent harmonic regulation of the controller. The most challenging test of the system's THD performance was performed at no-load and then compared to partial/full load performance as shown in the transient response test of Fig. 8.

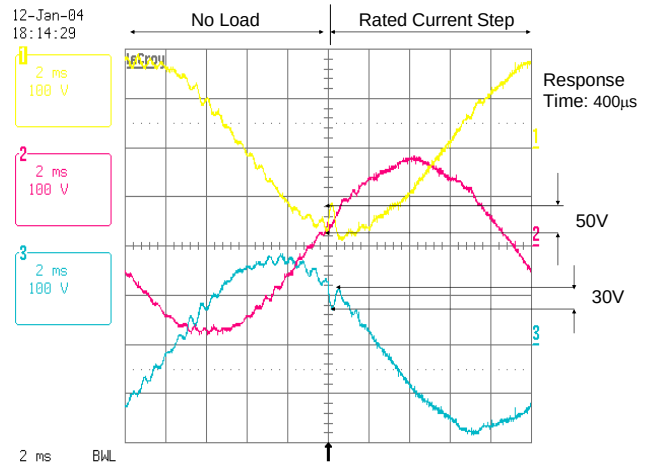


Fig. 8. System voltage response under step load, 120V line-line, 50Hz output.

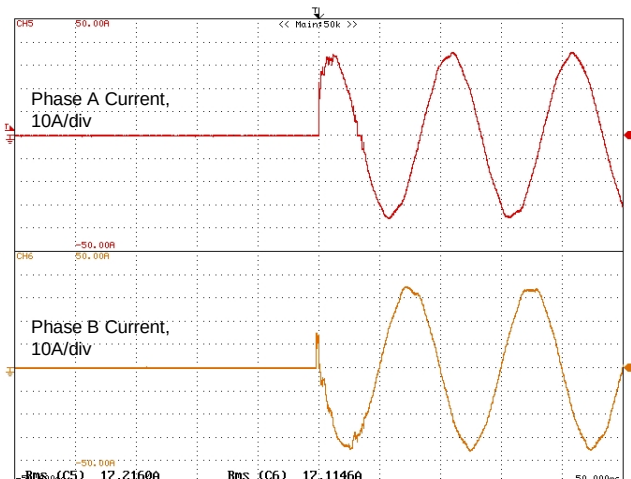


Fig. 9. Step resistive load response, near full load current at reduced output voltage.

The output current into a resistive load during the transient also demonstrates both aspects of the controller. Initial response to the step resistive load shows evidence of immediate control of output voltage; however it takes about a half a fundamental period to stabilize the lower frequency components of the controller. These components exist at about 360Hz, or six times the fundamental input frequency. These disturbances reveal that all non-linearities introduced by the matrix converter are not completely resolved by the GA solution in the compensator.

Military specifications require a THD analysis at rated output load. The analysis was carried out on a power analyzer with the matrix converter set to 120VAC, 50Hz. The results of a steady state load at rated current shows an impressive 0.38% THD. Fig. 10 shows a summary of the THD as a function of load.

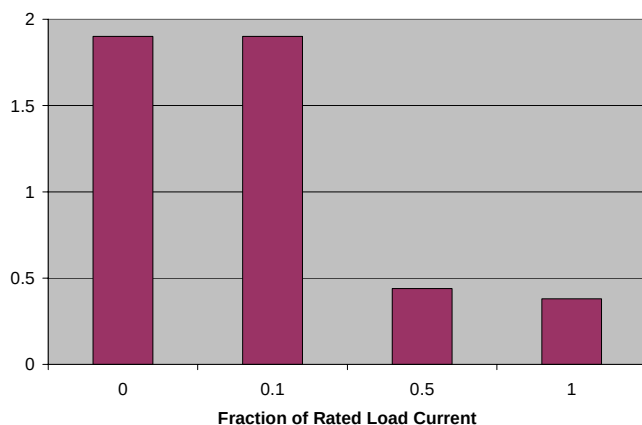


Fig. 10. Total harmonic distortion of output voltage measured at various load currents, (Resistive load).

VII. CONCLUSIONS

A matrix-converter based three-phase utility power supply has demonstrated success operating well within its specified harmonic distortion and transient response. The use of a matrix converter is also found to be relevant given its voltage transformation ratio and the flexibility within the generator for specific higher voltage wound alternators. The use of genetic algorithms has demonstrated that high bandwidth control loop design is possible with a single voltage loop. Controller performance has revealed a few improvements that still need to be investigated, such as steady state voltage regulation. Further work will investigate the development of an additional phase for control of unbalanced loads.

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