# PQSoft Case Study

## A Single-Phase 25 Hz Frequency Converter for the New York Metro 25 Hz Signaling Network


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| Customer Type | City | | |
| Miscellaneous1 | Single-Phase System | Sliding Mode Control | IGBT Based Converter |
| Miscellaneous2 | 25 Hz | Static Frequency Converter | |
| References | IEEE Std. 519 | | |


## Abstract:


This case study describes a static frequency converter (60Hz three-phase to 25Hz single-phase). This IGBT based converter supplies a signaling network used in the New York transit system and must be capable of withstanding various operational restraints such as, 25Hz signaling network short-circuits, non-linear loads and parallel operation with other sources.

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# RELATED STANDARDS

IEEE Std. 519

# INTRODUCTION

Historically in New York City, the use of single-phase 25Hz networks was relatively common place. The use of such networks is today very limited and the supply authority is faced with a greatly reducing number of customers. In addition, the generators originally installed to supply these networks are reaching the end of their useful lifetime. The few remaining customers for such networks, notably the transit authority, are having to pay inflated tariffs and in some cases penalties to the supplier for the continued use of their network. This has led to the requirement for 3 phase 60Hz to single phase 25Hz static frequency converters.

Such equipment is often connected to the 60Hz domestic networks of the city and the single phase output may run in cabling ducts over considerable distances (10Km) to power a large variety of signaling equipment. For these reasons the application of strict harmonic limits, as outline in the IEEE Std. 519, are necessary. Many of the single phase loads are non-linear, this coupled with the requirements of IEEE Std. 519 leads to the need to employ active filtering functions to maintain voltage harmonics within their limits. Due to the nature of the single phase distribution system relatively high levels of load can be applied instantaneously. This leads to the requirement for a highly dynamic control system which in addition must ensure that fault current levels are limited during system short circuits to ensure correct protection co-ordination. Finally, parallel operation of system substations must be ensured in all operating conditions including ground fault detection.

# SYSTEM OUTLINE

A schematic diagram of a number of substations along with their distribution system is shown in Figure 1.

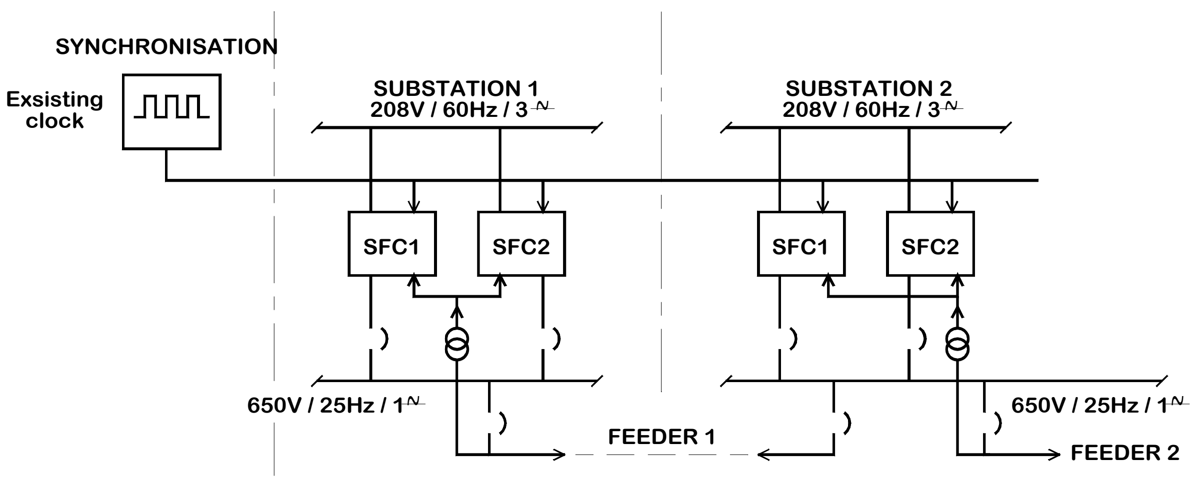


**Figure 1 – Substation Distribution System**

For redundancy reasons, two frequency converters are located at each substation. In normal operation, both frequency converters in the same substation are operated in parallel, load sharing to within 5%. Should one of the converters fail, the load is immediately picked up by the other frequency converter without any disturbance to the operation of the signal network. Signal feeders are normally fed from their respective substations. It is possible to parallel substations by closing breakers at both extremities of the feeder. In a similar way, to ensure substation redundancy, any given substation may power multiple feeder lengths thus increasing the substations load considerably in such contingency conditions.

Since substations must operate in parallel, a synchronization system must be employed which works correctly in all operational modes of the system. Due to the long distances between substations and the lack of free cabling between them, it is not possible to distribute an analogue phase reference. Converters are frequency synchronized using an existing fixed frequency clock signal previously used to synchronize PLC type equipment within the metro system. Analogue feeder voltage feedbacks in each substation may be used to phase lock the substations together.

During earth fault finding conditions, personnel will enter the metro tunnels and manually open field switches along the feeder whilst two substations are operating in parallel thus isolating the substations from one another. The analogue feedback within the substation can no longer be used to phase synchronize the equipment. Phase shifting is avoided however, due to the use of the existing fixed frequency clock signal.

## CONVERTER DESIGN

The equipment design is shown in the single line diagram of Figure 2.

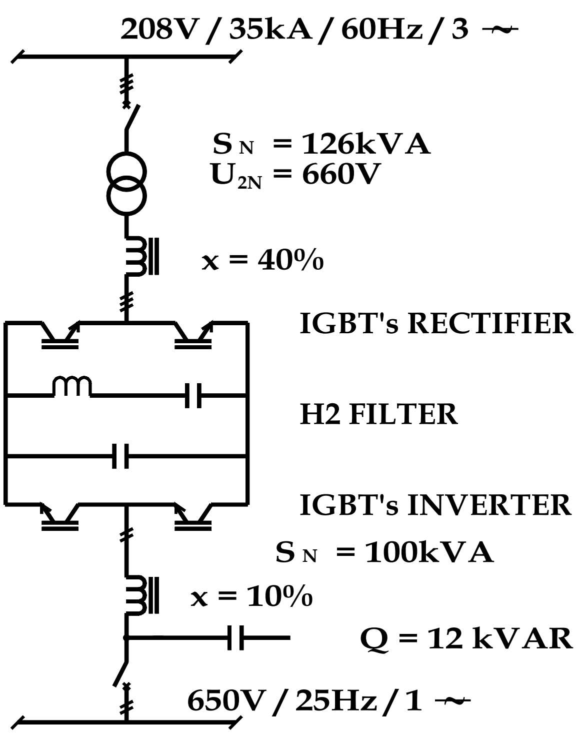


**Figure 2 – Equipment Schematic Diagram**

From this it can be seen that, to ensure low harmonic levels at the three phase point of connection with the 60Hz supply a classic sinusoidal IGBT based converter is used [1]. To ensure that 50Hz harmonics, resulting from the 25Hz single phase load, are not injected onto the input supply, a tuned 50Hz filter is placed in parallel with the DC link capacitors of the frequency converter.

The output bridge of the equipment is again based on IGBT technology used in an H bridge configuration. To ensure both the filtering of the output switching frequency and to allow for the connection of high levels of non linear load, an undamped output filter is used and damping is ensured by the control system of the frequency converter.

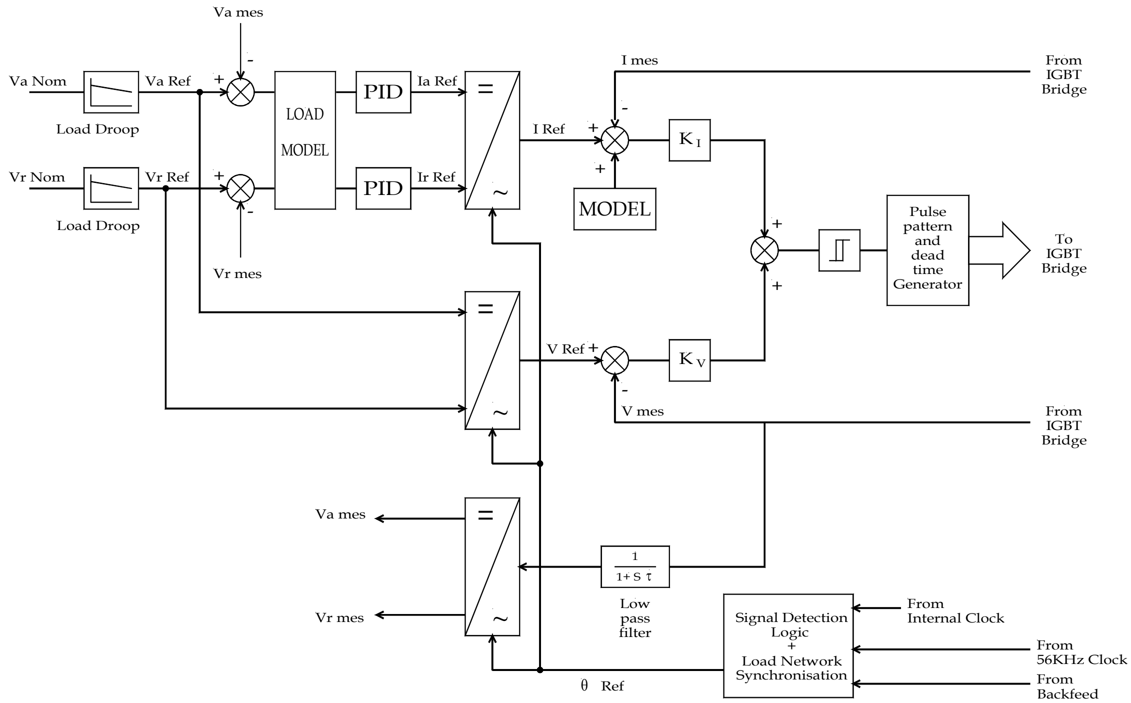


**Figure 3 – Control System Block Diagram**

Figure 3 shows a block diagram of the control system.

A sliding mode controller is used to ensure the damping of the output filter along with the necessary active filter function to ensure a sinusoidal output voltage in the presence of large nonlinear loads [2]. The control of the output voltage is based on a static a/r reference frame in which the a axis represents the active voltage and r the reactive. This can be presented as shown in Figure 4.

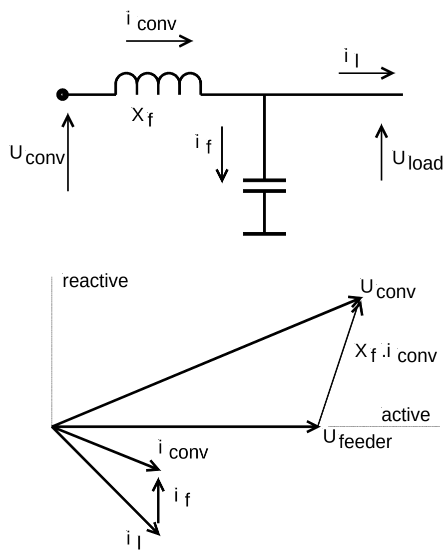


**Figure 4 – Output Phasor Diagram**

Voltage droop is included to ensure good load sharing. The error between reference and measured values of the a/r voltages are then applied to the PI regulators for the active and reactive currents via a load identification matrix to ensure correct cross coupling of a and r axes for all load conditions. The thus generated references for current and voltage on the a and r axes are then transformed into instantaneous AC references. These references are then compared to their respective measured values. A pass band filter is used to remove all fundamental errors of the output voltage. In this way, the voltage loop controls merely harmonic voltages and it is the current loop which is responsible for regulating the fundamental current. To ensure high dynamics, a load current model is summed with the reference, this uses output voltage and converter output current to derive the instantaneous load current.

## EXPERIMENTAL RESULTS

The equipment previously outlined, was install in the metro system. Based on a modular design for ease of installation, the equipment is spilt into 3 cubicles. One containing the 208V/660V 126kVA transformer and input bridge supply reactor. The second containing the 2 IGBT power modules, DC link filtering, Control electronics and divers auxiliary equipment. The third and final cubicle contains the output filter. The control system is implemented on an Intel 960CA 32 bit 33MHz RISC processor in conjunction with a sliding mode control pcb developed specifically for this application.

Figure 5a shows the input current and voltage when the equipment is operating at full load current. One can also see in Figure 5b the spectral analysis of the current.

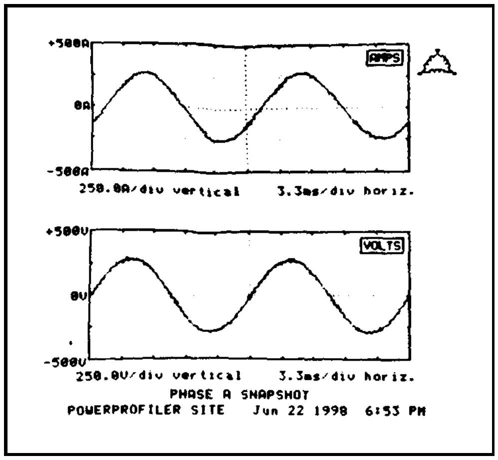


**Figure 5a – Input Current and Voltage at Full Load**

PHASE B CURRENT SPECTRUM 6:52:05 PM

Max load current: 100 A rms

Fundamental freq: 60.0 Hz

| HARM | PCT | SINE PHASE | HARM | PCT | SINE PHASE |
|---|---|---|---|---|---|
| FUND | 193.8% | -122' | 2nd | 1.9% | -150' |
| 3rd | 2.5% | 3' | 4th | 0.6% | -67' |
| 5th | 0.4% | 19' | 6th | | |
| 7th | 0.8% | 139' | 8th | 0.1% | -91' |
| 9th | 0.1% | -45' | 10th | | |
| 11th | 0.3% | -108' | 12th | | |
| 13th | 0.2% | -5' | 14th | | |
| 15th | | | 16th | | |
| 17th | | | 18th | | |
| 19th | | | 20th | | |
| 21st | | | 22nd | | |
| 23rd | | | 24th | | |
| 25th | | | 26th | | |
| 27th | | | 28th | | |
| 29th | | | 30th | | |
| 31st | 0.2% | -161' | 32nd | | |
| 33rd | | | 34th | | |
| 35th | | | 36th | | |
| 37th | | | 38th | | |
| 39th | | | 40th | | |
| 41st | | | 42nd | | |
| 43rd | | | 44th | 0.2% | -42' |
| 45th | 0.3% | 74' | 46th | 0.2% | 46' |
| 47th | 0.3% | -173' | 48th | | |
| 49th | | | 50th | 0.2% | 76' |
| ODD | 2.7% | | EVEN | 2.0% | |

TDD: 3.4%

Figure 5b – Input current spectral analysis

One can note from these results the extremely low levels of input harmonics resulting from the use of the Sinusoidal IGBT input rectifier switching at 3khz and with an input reactor of approximately 40%. Figure 6a shows the output current and voltage when the equipment is operating at approximately 20% of full load current. Figure 6b and c shows the spectral analysis of these waveforms.

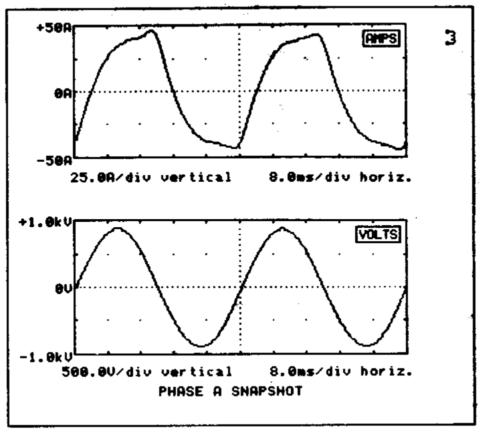


**Figure 6a – Output current and voltage**

PHASE A VOLTAGE SPECTRUM 9:39:38 AM

Fundamental volts: 631.7 Vrms

Fundamental freq: 25.0 Hz

| HARM | PCT | SINE PHASE | HARM | PCT | SINE PHASE |
|---|---|---|---|---|---|
| FUND | 100.0% | 0° | 2nd | 0.1% | -25° |
| 3rd | 1.0% | 89° | 4th | | |
| 5th | 0.3% | 97° | 6th | | |
| 7th | | | 8th | | |
| 9th | | | 10th | | |
| 11th | | | 12th | | |
| 13th | | | 14th | | |
| 15th | | | 16th | | |
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| 29th | | | 30th | | |
| 31st | | | 32nd | | |
| 33rd | | | 34th | | |
| 35th | | | 36th | | |
| 37th | | | 38th | | |
| 39th | | | 40th | | |
| 41st | | | 42nd | | |
| 43rd | | | 44th | | |
| 45th | | | 46th | | |
| 47th | | | 48th | | |
| 49th | | | 50th | | |
| ODD | 1.1% | | EVEN | 0.1% | |

THD: 1.1%

Figure 6b: Output voltage spectrum

PHASE A CURRENT SPECTRUM 9:39:42 AM

Fundamental amps: 32.58 A rms

Fundamental freq: 25.0 Hz

| HARM | PCT | SINE PHASE | HARM | PCT | SINE PHASE |
|---|---|---|---|---|---|
| FUND | 100.0% | -39° | 2nd | | |
| 3rd | 14.5% | -77° | 4th | | |
| 5th | 4.4% | -63° | 6th | | |
| 7th | 1.8% | -53° | 8th | | |
| 9th | 0.7% | -57° | 10th | | |
| 11th | 0.3% | -62° | 12th | | |
| 13th | | | 14th | | |
| 15th | | | 16th | | |
| 17th | | | 18th | | |
| 19th | | | 20th | | |
| 21st | | | 22nd | | |
| 23rd | | | 24th | | |
| 25th | | | 26th | | |
| 27th | | | 28th | | |
| 29th | | | 30th | | |
| 31st | | | 32nd | | |
| 33rd | | | 34th | | |
| 35th | | | 36th | | |
| 37th | | | 38th | | |
| 39th | | | 40th | | |
| 41st | | | 42nd | | |
| 43rd | | | 44th | | |
| 45th | | | 46th | | |
| 47th | | | 48th | | |
| 49th | | | 50th | | |
| ODD | 15.3% | | EVEN | 0.1% | |

THD: 15.3%

Figure 6c: Output current spectrum

Again note the extremely low levels of voltage harmonic despite the presence of relatively high levels of third harmonic in the output current. This is the result of the use of the sliding mode regulator. In addition to its harmonic performance, Figure 7 shows the output current and voltage at a load impact of 30%.

Load
current
100A/div

**Figure 7 – 30% Load Impact Respor**

The voltage falls by less than 10% and the transient lasts only 20mS. Th dynamic nature of the control system. Figure 8 illustrates the synchronization between converters for which a phase synchro signal is used along with a fixed frequency clock.

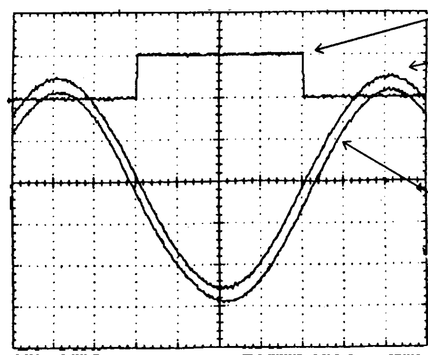


**Figure 8 – Phase Synchronization between Converters**

Finally, in Figure 9, one can see the output voltage and current during a short circuit.

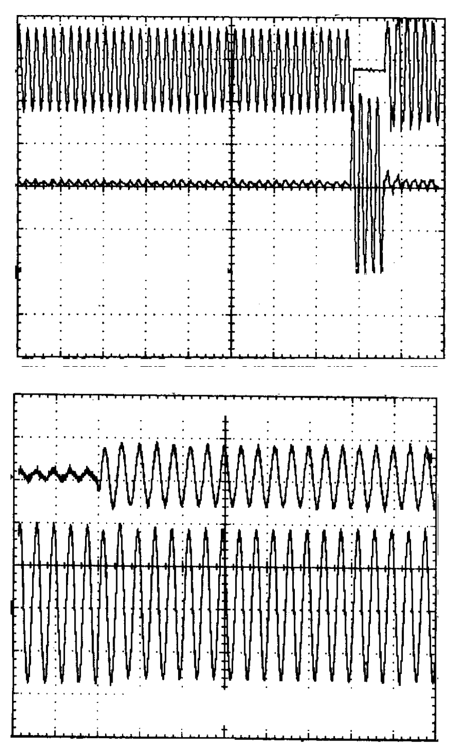


**Figure 9 – Short Circuit Performance**

In this case the output current is limited to 360Arms and should the short circuit remain, after 2 Seconds the equipment will trip. In this case, however, we see that the individual circuit which is shorted, is isolated by a protection breaker and the output voltage is re-established for the rest of the out load.

## SUMMARY

The paper has presented the design of a three phase to single phase static frequency converter which satisfies the following design criteria:-

- Low three phase input harmonics.
- High quality of the output voltage even in the presence of non-linear loads ( an active filter function ). This effectively mimics a high Pcc supply source, which in the absence of the active filter function would not be possible for a frequency converter of only 100kVA.
- Load sharing between frequency converters within the same substation and parallel operation between substations. (This being true when both are FC powered substations and between FC and alternator powered substations ).
- Short circuit current limitation. Re-establishment of the output voltage after the short circuit is isolated.
- High dynamic performance when the load is suddenly applied or removed.

## REFERENCES

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2. K. Sahnouni, O. Lapierre, S.R. Jones, A. Berton. A Shunt active filter with a sliding mode control circuit. EPE. Trondheim 1997.