# Modeling and Analysis of a 1.7 Mva SMES-based Sag Protector

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*Abstract* – The objective of this paper is to present the modeling and analysis of a 1.7 Mva SMES-based voltage sag corrector devices. The topology of the SMES-based system and its response to an upstream fault are described. This paper details various modeling aspects of the device including methods to generate a triangular signal and an internal reference voltage. Models to characterize the harmonic contribution during the idling mode are presented. Simulation in both idling and carryover mode are conducted.

**Keywords:** SMES-based sag protector, time domain analysis, modeling.

## I. INTRODUCTION

Power quality problems generally appear in the form of voltage sags, transients, and harmonics. From these three broad categories of power quality problems, voltage sags account the most disturbances experienced by industrial customers. Voltage sags generally refers to instantaneous short-duration voltage variations. Typical duration of voltage sags is between 0.5 to 30 cycles with typical magnitude of 0.1 – 0.9 per-unit. The consequences of voltage sags to sensitive loads can be severe, such as production losses, scrap product, plant shutdown, and unnecessary maintenance to mention just a few examples.

Many solutions have been proposed to mitigate voltage sags. In principle, these solutions can be divided into two approaches, to redesign the sensitive equipment such that it does not trip out during a sag event, or to maintain the supply voltage at a nominal level, i.e., one per-unit level at all time. In this paper, we focus on a device-based superconducting magnetic energy storage (SMES) technologies to maintain load voltage at one per-unit. This device is commonly known as a sag protector, or dynamic voltage restorer, or power quality voltage restorer. In particular, we focus on a 1.7 Mva superconducting magnetic energy storage (SMES) power quality voltage restorer (PQ-VR).

Section II of this paper describes the state-of-the-art and operation of the PQ-VR. It will describe the super-conducting magnetic energy storage system, voltage regulator, DC/DC converter, inverter, and the injection transformer. Operation and control of the PQ-VR system during the idling and carryover modes will also be described. Since one or more PQ-VR components are power-electronics based, the PQ-VR may contribute a small amount of harmonic distortion to the distribution system where it is installed. Therefore, this paper will also predict the total harmonic contribution due to the presence of the PQ-VR in the system.

In order to predict the harmonic contribution, the detail PQ-VR model is developed and simulated using PSCAD/ EMTDC software. A distribution system consisting of the PQ-VR, a series-injection transformer, nonlinear loads, and a substation will be modeled. PQ-VR harmonic characteristics during the idling mode, along with the PQ-VR performance during the carryover mode, will be presented.

## II. PQ-VR: SMES-BASED SYSTEM

One of the most basic properties of superconductor materials is the ability to give up electrical resistivity. Therefore, superconductors carry electricity without energy loses, as most conductors do. The SMES-based system was developed to take advantage of this property. The electric energy is stored in the form of current flowing endlessly around a superconducting coil of wire maintained at its operating temperature. Since the coil is lossless, the energy can be released almost instantaneously. With an appropriate mechanism, this energy can be injected into an electrical system to boost voltage when needed such as during faults at a nearby distribution/transmission system. This mechanism is carried out by a PQ-VR.

Figure 1 shows the functional block diagram of a PQ-VR. It consists of a superconducting magnet, voltage regulators, capacitor banks, DC-DC converter, DC breakers, inverter modules, sensing and control, and a series-injection transformer.

The superconducting magnet shown in Figure 2 is constructed of NbTi (niobium titanium) conductor and is cooled to approximately 4.2 K by liquid helium. The cryogenic refrigeration system is based on a two-stage recondenser. The magnet electrical leads use HTS (high temperature superconductor) connection to voltage regulator and controls. The magnet stores about 3 MJ.

Energy realeased from the SMES passes through a current-to-voltage converter to charge a 14 mF (typical) DC capacitor bank at 2,500 Vdc. The voltage regulator keeps the DC voltage at its nominal and also provides protection control to the SMES.

The DC/DC converter reduces the DC voltage down to 750Vdc. The inverter subsystem module consists of six single-phase inverter bridges. Two 450 Arms rated inverter bridges are paralleled in each phase to provide a total rating of 900 Arms per phase. The inverter bridge is based on IGBT technologies and operates at a DC bus voltage of approximately 750 Vdc. The switching scheme for the inverter is based on the pulse width modulation (PWM) approach where the carrier signal is a sine-triangle with frequency of 4 KHz.

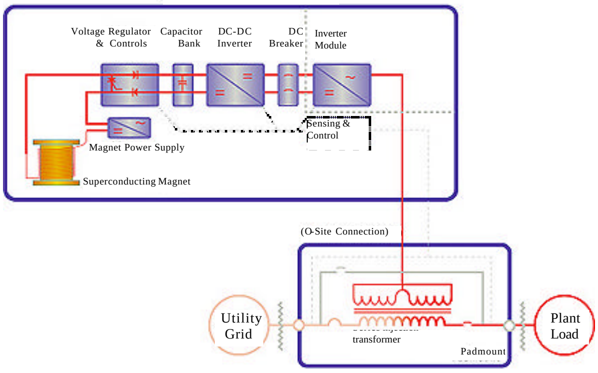
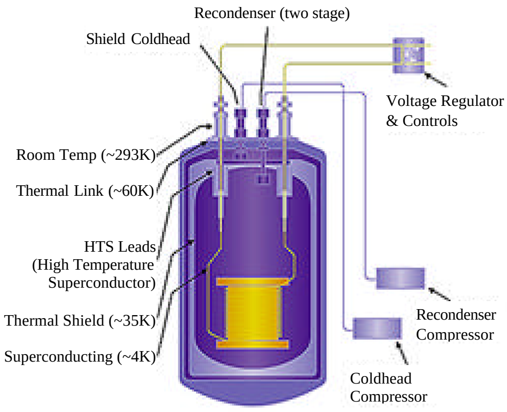



Figure 1 – Typical PQ-VR functional block diagram
Figure 2 – Superconducting magnet and its components




The operation of the PQ-VR is controlled by a digital controller embedded in the inverter module. When the utility grid voltage is at a nominal 1.0 per-unit, the PQ-VR is in the idling or standby mode. A sag detection algorithm continuously compares the grid voltage to the expected voltage. During the idling mode, a servomechanism algorithm regulates the inverter current to drive the load voltage to the utility grid voltage. When the utility voltage falls outside the expected voltage envelope, the controller initiates transition to a carryover mode. Immediately following the transition, the reference voltage for the servo is transferred from the grid to the PQVR internal reference voltage. The internal reference voltage is magnitude- and phase-synchronized to the grid voltage prior to the transition. The inverter current now draws energy from the DC link capacitor. The voltage regulator and controls determine the magnet discharge rates necessary to maintain the inverter DC link voltage. When the grid voltage returns to its nominal 1.0 per-unit value, the PQ-VR internal reference is resynchronized to the grid, and the servo reference voltage is switched back to the grid voltage and back to the idling mode.

## III. PQ-VR Modeling

In this section we focus on modeling the PQVR system. The system is installed to protect sensitive electronic equipment. A three-phase model of the customer facility and the PQ-VR system were developed using the PSCAD/EMTDC software. Note that the models described below are simplified versions of the actual PQ-VR. Some control schemes presented in this paper might not be identical to the actual ones, however, they perform the same functions.

The overall PQ-VR and its distribution system models are shown in Figure 3. The utility grid or substation is modeled as an equivalent source characterized by the positive and zero sequence impedances. The PQ-VR system is protected, among other protection schemes, by the input and output breakers at the grid and load sides respectively, and the bypass breaker. These breakers are also used for PQ-VR maintenance purpose. The plant load can be modeled as a harmonic injection source when determining the total harmonic contribution by the PQVR during the idling mode. However, it should be modeled as conventional linear or nonlinear loads when studying the performance of the PQVR during the carryover mode.

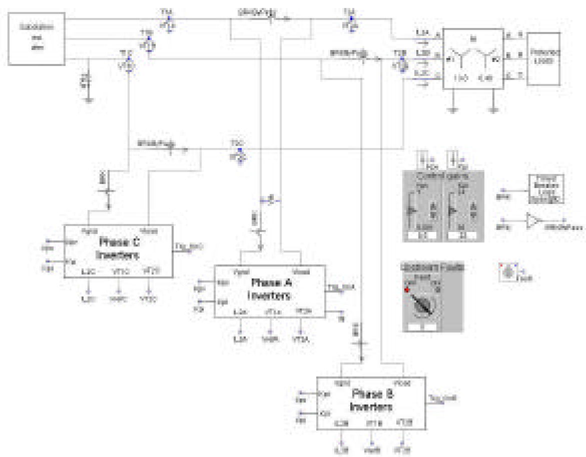



Figure 3 – The overall PQVR system modeling

Figure 3 shows inverter modules for phases A, B, and C ("Phase A Inverters", "Phase B Inverters", and "Phase C Inverters"). The details of these inverter modules are shown in Figure 4. Two single-phase inverter bridges are paralelled through a series injection transformer providing a total rating of 900 A. Each inverter bridge is rated at 450 A. The high-voltage side of the injection transformer is connected to the load side, while the low-voltage side is connected to two H-bridge modules.

In modeling the PQVR, it is assumed that the DC Link capacitor bank is always maintained by the voltage regulator to a constant DC voltage of 750 V. This is a legitimate assumption since the SMES can discharge instantaneously such that it always maintained the DC voltage link at 750 V at all time until the SMES energy is exhausted. With this assumption, the input of the inverter bridge can be modeled as a DC voltage source. Figure 5 shows a typical inverter bridge.

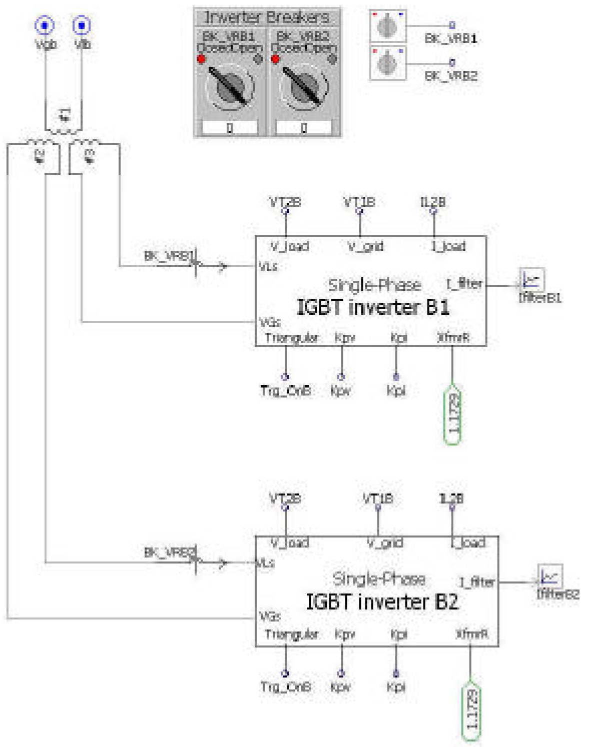



Figure 4 – PQ-VR inverter modules connected in series to a distribution system.

The inverter bridge consists of four IGBTs which turn on-and-off according to commands generated by a PWM controller. The switching scheme is performed by comparing the grid voltage and its expected voltage on an instanteneous waveform basis (i.e., it is not based on RMS basis) resulting in an error signal. The error signal is then compared to a 4-KHz sine-triangle carrier signal to produce commands to switch the IGBTs on and off. In developing the model, the IGBT component is modeled as an ideal power electronics switch. The on and off resistance is set to 0.01 and 1.0 million ohms, respectively. The forward voltage drop, forward breakover voltage, and the reverse withstand voltage characteristics are set to 0 kV, 100 kV, and 100 kV, respectively

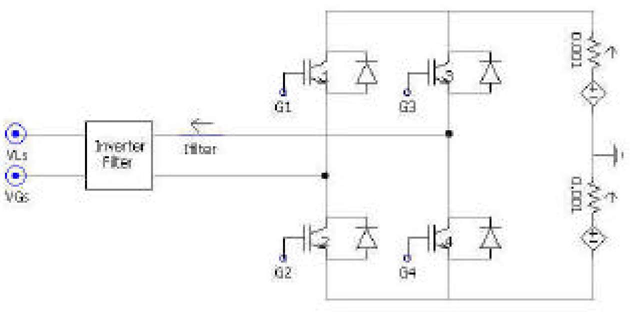



Figure 5 – PQ-VR inverter bridge.

Figure 6 shows the 4-kHz sine-triangle carrier signal is generated using a phase-lock-loop controller synchronized to the grid voltage (Va, Vb, Vc at the input of "PLL Six Pulse"). A multiplier of 66 is applied to the output of the PLL to create a 4-kHz carrier signal. A modulus of 360 is so applied such that the phase angle of the carrier signal is always between 0 and 360 degrees. A modulus is a reminder after division.

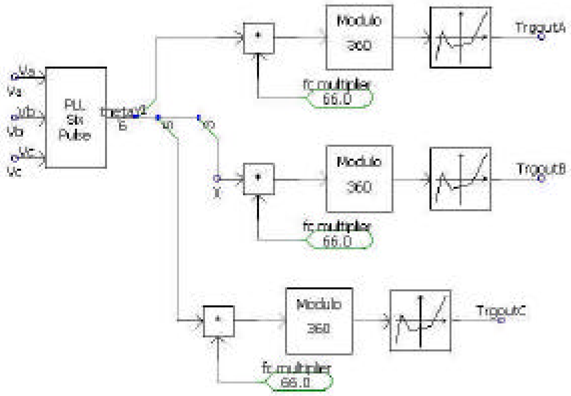
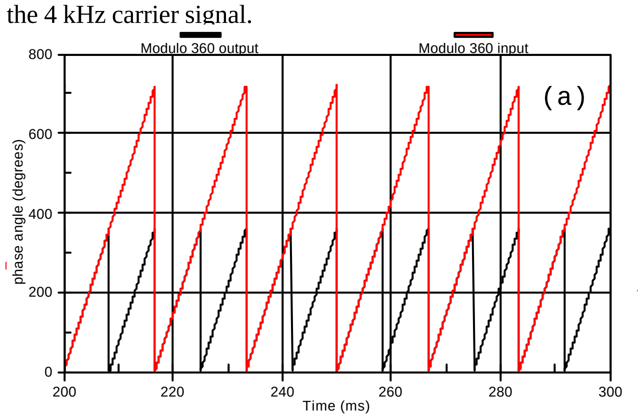



Figure 6 – Generating the 4kHz sine-triangle carrier signals.

In order to help understand the above process, let us for a moment simplify and assume the carrier signal is only 120 Hz or twice the fundamental frequency. The input sinusoidal waveform (only one phase is shown) to the PLL module is shown in Figure 7b. The output of the PLL is the phase angle of the sinusoidal waveform. At the positive-going zero crossing of the sinusoidal waveform, the phase angle is zero, at the negative-going zero crossing the phase angle is 180 degrees, and at the next immediate positive-going zero crossing the phase angle is 360 degrees or zero degree. Therefore the phase angle ranges from 0 to 360 degrees. The phase angle signal coming from the PLL module is then multiplied by a factor of two to generate a 120 Hz right-triangle waveform. Figure 7a shows a right-triangle waveform with phase angles from 0 to 720 degrees. This signal is fed to the "Modulo 360." The output of "Modulo 360" is shown in Figure 7a where the right-triangle waveform ranges from 0 to 360 degrees. A simple transfer function is applied to generate an isosceles (or sine-triangle) waveform shown in Figure 7b. The transfer function maps 0, 180, and 360 degrees to magnitude of 0, 1, and 0. The above procedure illustrates the generation of the 4 kHz carrier signal.



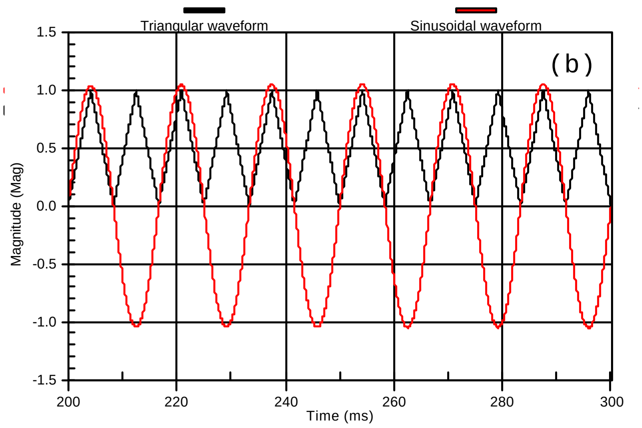



Figure 7 – The carrier frequency is twice the fundamental frequency. (a) Input and output of the module 360 block, (b) The sine-triangle waveform is synchronized to the grid voltage waveform.

It was mentioned above that when the grid voltage falls outside the envelope of the expected voltage, the reference voltage for the servo is transferred from the grid to the internal reference voltage. This internal reference voltage must be phase-lock-loop and synchronized to the grid voltage prior to a voltage sag event. There are several ways of generating the internal reference voltage. The simplest one is to take an FFT of one or two cycles prior to a sag event. The internal reference voltage can be generated using the magnitude and phase angle of the fundamental frequency. Figure 8 shows how the internal reference voltage is generated (only one phase is shown).

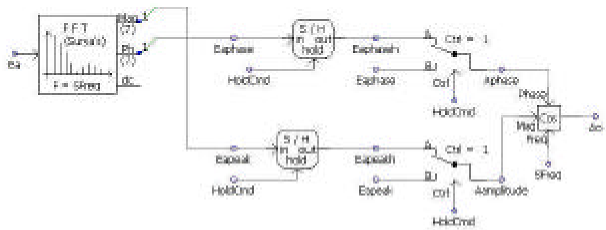


**Figure 8 – Generating an internal reference voltage.**

## IV. SIMULATION RESULTS

In this section we simulate the operation of the PQ-VR and determine its harmonic contribution to the local distribution system.

In characterizing the harmonic contribution during the idling mode, the background harmonic producing load is modeled as a current injection source. In this simulation, the harmonic load is represented with the following characteristics, 1.0%, 3.5%, 2.5%, 1.0%, 0.5%, 0.5%, 0.38%, 1.13%, and 0.75% for the 3rd, 5th, 7th, 9th, 11th, 13rd, 15th, 17th, and 19th harmonics, respectively. The total THD current is then 4.8%. The PQ-VR is initially turned off. The THD voltage at the load side of the series injection transformer is approximately 0.7%. At time 0.1 seconds following the start of the simulation, the PQ-VR is switched on. The THD voltage increases to 2.3% due to the switching transient before it finally settles down at 0.7%. Therefore the THD voltage essentially remains the same with and without the PQ-VR in the distribution system. It means with proper inverter filter configuration the harmonic produced by the PQ-VR will not propagate into the distribution system. Figures 9 and 10 show the inverter current flowing towards the inverter filter (as shown in Figure 5) and the THD voltage at the load side of the series injection transformer, respectively.

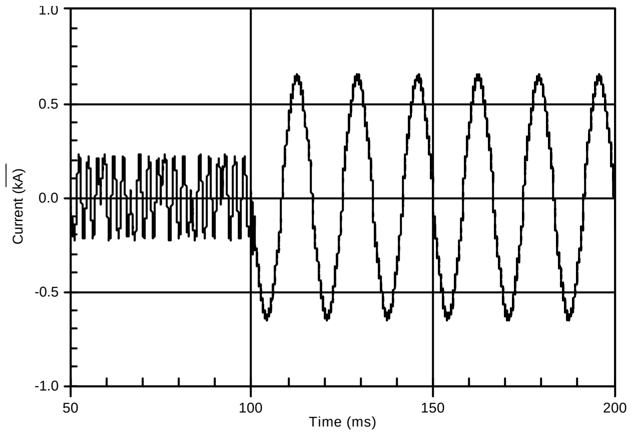



Figure 9 – Inverter current flowing towards the inverter filter.

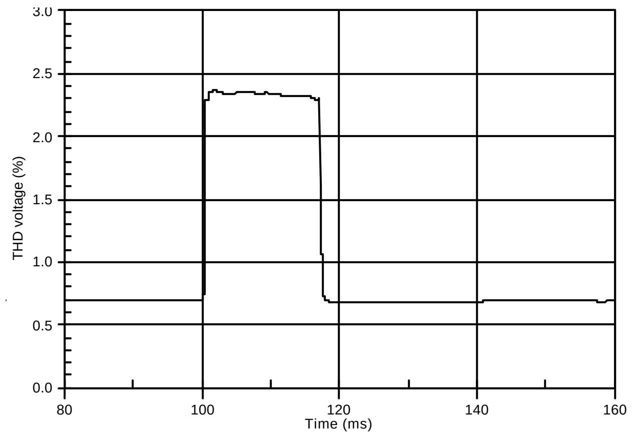



Figure 10 – THD voltage at the load side of the series injection transformer.

When simulating the PQ-VR in carryover mode, the harmonic producing load cannot be modeled as a current injection source. Instead it must be modeled as a conventional nonlinear load such as a six-pulse rectifier or other combination of linear and nonlinear loads. If the load is represented with the injection current source, the carryover mode cannot be simulated properly since the current flowing to the load remain constants. In this simulation, the load is modeled as a six-pulse rectifier.

The carryover mode is simulated by applying a fault upstream from the PQ-VR. A single-line to ground fault is applied at approximately 290 msec following the start of the simulation and lasts for about six cycles. Figure 11 shows the grid and load side voltages. The grid voltage sags to 0.7 per-unit. The PQ-VR successfully holds the load side voltage at 1.0 per-unit.

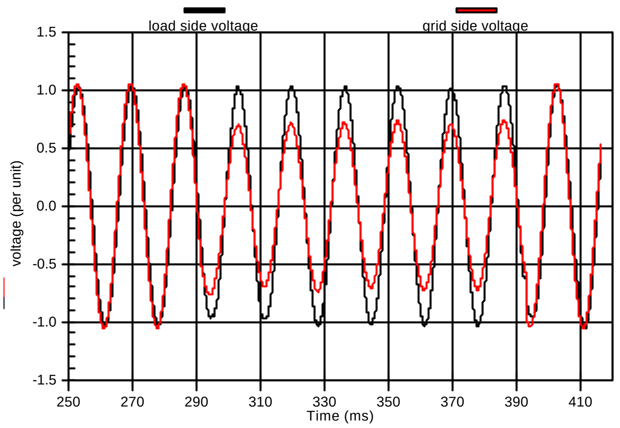



Figure 11 – PQ-VR in carryover mode. The voltage sag is at the grid side. The load side voltage remains at 1.0 per-unit since the PQ-VR successfully holds the voltage.

## V. SUMMARY

This paper presents an example of modeling a voltage sag corrector device such as a DVR or a PQ-VR. The example presented is sufficiently general and can be applied to model other types of sag corrector devices. Power electronic switches along with its switching strategy, and internal reference voltage can be easily developed using the PSCAD/EMTDC software.

In characterizing harmonic contribution when the PQ-VR is in idling mode, nonlinear harmonic loads can be represented with a current injection source. However, when analyzing the operation characteristics during the carryover mode, the nonlinear harmonic loads can no longer be represented with the current injection source. Instead, it must be represented with a conventional nonlinear load such as a six-pulse rectifier or other equivalent representations.

## VI. REFERENCES

[1] M. R. Behnke, W. E. Buckles, R. M. Hudson, "Development and testing of a 1.7 MVA superconducting magnetic energy storage based sag protector," *Electical Energy Storage System Applications & Technologies, 1998 International Conference, Chester, United Kingdom, June 16-19, 1998.*