A Virtual Test Bed for Power Quality Solutions

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Abstract—The Virtual Test Bed (VTB) software provides a publicly accessible environment for testing of power quality solutions. The VTB supports multi-lingual and interactive simulations as well as advanced visualization techniques. Multi-lingual capabilities of the VTB include interfaces with Matlab/Simulink, Labview, ACSL, Pspice. These interfaces are highly beneficial in many aspects including development, implementation and rapid prototyping of various control algorithms at all levels from low level device controllers to high level system or decision-making controllers. Advanced 3-D visualization and animation capability is invaluable for quick and precise comprehension of the simulation data. The visualization objects are linked to the real time simulation processes. Two-way communication between the visualization and simulation yields highly interactive simulation. For example, power converter modules can be turned "on" or "off" from within the visualization environment during simulation run-time. This action changes the circuit topology during the simulator run-time, which results in interactive simulation that closely models the behavior of a realistic physical system. Advanced capabilities of the VTB software are demonstrated on an application example that solves several power quality problems in AC zonal power system. Novel AC zonal control algorithm that ensures uninterrupted delivery of power to critical loads even despite the loss of portions of the power distribution network is developed, implemented in the VTB software and successfully tested. The VTB simulation proves that new control algorithm is not susceptible to high harmonics content typically present in some power systems.

***Index Terms*—Virtual Test Bed, Modeling, Simulation, Power Quality, Zonal Systems, Control, Cosimulation, Visualization.**

I. Introduction

POWER quality solutions are increasingly complex, the power system behaviors are dominated by control algorithms rather than by the physical structures, and the inherent behaviors of most system components are nonlinear. Hence, Power Quality problems are generally non-analytic so the investigation and resolution of such problems demands support from a simulation environment.

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The Virtual Test Bed software, which has been developed at the University of South Carolina during the past half-dozen years, is strongly suited to these sorts of problems. The environment offers the following capabilities that support Power Quality research and problem resolution:

- Variable time steps with event scheduling;
- Interface to Simulink;
- Interface to Labview;
- Rapid prototyping of controls;
- Capability to study AC or DC systems;
- Use of advanced diagnostics e.g. system identification toolbox.

In addition to these capabilities that specifically support power quality system analysis, other significant features of the VTB include:

- Graphical environment for definition of the system and for interaction during simulation runtime;
- Independent model format;
- Multiple views (graphical) of system components;
- Dynamically linked simulation models, allowing runtime changes to the simulated system;
- Graphical environment that supports both measurement-focussed graphics and conceptual or physics-based graphical system views;
- Diverse model library, supporting multidisciplinary system simulation;
- Capability for simulation with hardware in the loop;
- Realtime environment (option), running under Linux (as compared to human interactive version that runs under Windows);
- Scripting tool that recognizes the difference between realtime and runtime changes;
- Options to cosimulate with other software including Matlab/Simulink and Advanced Continuous Simulation Language.
- Multiple types of object ports, including those that enforce natural conservation laws and those that obey signal flow principles.

Figure 1 shows the user interface for the Schematic Editor which is used to define the system under study. A system is assembled by a drag and drop approach, selecting objects from the model library (list shown in left-most window). Model objects are not limited to the electrical discipline, but can instead be defined in other disciplines such as mechanical, fluid, thermal and so forth. Interconnection ports can be of type “natural” or “signal”.

The independent model format of the environment allows the model library to be upgraded independently from the other parts of the software. Furthermore, each object can use or define its own computational processes internally, reporting back to the structured environment only the minimal data necessary to solve for the behavior of the interconnected system.

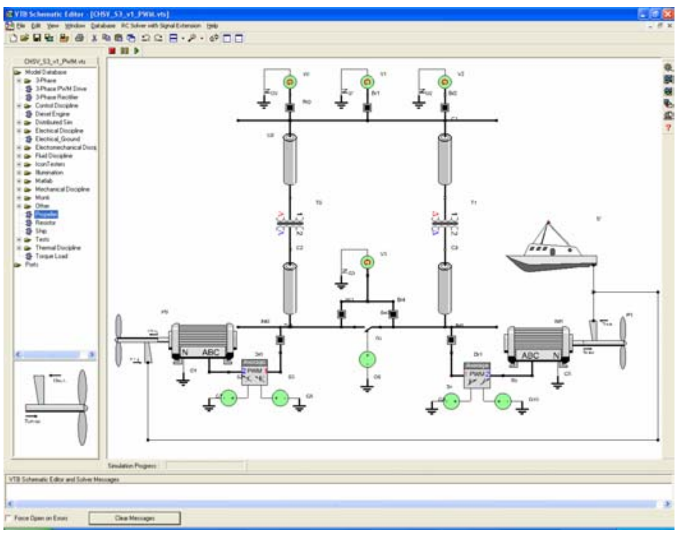

Figure1. VTB Schematic Editor User Interface

Models can have multiple “layers”, which may correspond to different views and/or to different mathematical representations. In the simplest implementation, the same object could be represented in different colors corresponding to a state or variable within the model. In more sophisticated implementations, the different layers can correspond to different levels of complexity in the model or to different forms of representation. Examples of the first case include representation of a power converter at three levels of detail such as 1) switching average model, 2) switching model with ideal switch, 3) switching model with non-ideal switch. Examples of the second case include showing power system entities in one-line representation or in 3-phase representation.

The architecture of the VTB requires that models be provided as dynamically linked software objects. Exposed user parameters can be adjusted during simulation runtime, either through dialog boxes or via controls (such as sliders) in the graphical output environment. This allows efficient human interaction with the simulation, which leads to quick assimilation of parametric dependencies.

The graphical output environment, VXE (Visualization eXtension Engine), allows the user to rapidly comprehend system performance. Visual outputs include data-driven animations of object motions, imposition of novel representations of abstract simulation data on top of solid objects, or just oscilloscope-like graphs. Bi-directional communication paths between the graphics environment and the simulation environment allow objects in the graphical environment to control parameters in the simulation environment, and vice-versa.

Besides electric system objects, models within the VTB environment can represent any object where natural coupling laws apply. Generally lumped element models are used, but otherwise more complex models such as finite element models can be used. For example, the software is heavily used on projects that include fluid and thermal analyses such as fuel cell systems.

When running under the Windows operating system, the software allows human interaction at arbitrary simulation speeds, either faster or slower than clock time depending on the capabilities of the processor, the complexity of the problem, and the nominal time step. For systems that are capable of running faster than realtime, a soft realtime option can be invoked that forces the simulation speed to correspond with clock time. This soft realtime feature is useful to make the interaction and visualization appear realistic when a simulation is driving animations that require operator interaction.

Hard realtime operation with fast time resolution can be achieved by running the simulation under a Linux operating system with realtime controls. Running under such a system is as easy as defining the system on a computer that runs the Windows operating system, then saving the system definition file (*.vts) to a mapped network drive on the Linux computer. Starting the simulation on the Linux computer (by reading the *.vts file) allows the simulation to interact with external hardware – either digital equipment (which we call “processor in the loop”, or analog equipment (which we call “power in the loop”. “Processor in the loop” is valuable for rapid prototyping of digital controls (see later), while “power in the loop” is valuable for incremental virtual prototyping – incremental substitution of real hardware for components of the simulation model. This incremental substitution of real hardware allows one to test the overall system with the best possible representations of the immediately available system components – the components themselves!

The scripting tool, which is not yet a mature part of the software, allows one to define a simulation script in two ways. One simple scripting method allows to record every user action during runtime so that the simulation to be played back again later following the same actions. The other method allows apriori definition of the script through a separate script editing environment. The VTB scripting environment introduced a new concept to scripting – identification of actions as either runtime actions or realtime actions. The distinction is very important but somewhat subtle. A realtime event must occur at precisely some instant relative to wall clock time so that it properly interacts with hardware (if any is tied into the simulation problem) or the user (if a user expects something to happen at e.g. 5 seconds after the simulation starts), whereas a runtime action may occur when the simulation time marker crosses some specific threshold even if that threshold does not correspond to clock time. For example, a fault might be applied to a power distribution conductor 135 ms after a simulation starts. If the simulation had a constant 5 microsecond time step, then the action should occur at the 71st time step, regardless of how much wallclock time had passed before the simulation took the 71st time step.

Interface objects allow the VTB solver to cosimulate with other executable objects, which can be stand-alone code or other user software. Two particularly valuable environments are the Matlab/Simulink environment and the Advanced Continuous Simulation Language environment. The Simulink interface is available in two forms – one which allows cosimulation with the Simulink engine and hence requires the simulationist to own a Matlab/Simulink license and another which allows cosimulation with a compiled form of the model, which does not require the simulationist to own a form of the model. The compiled form of the model is exported from Simulink using the toolset from the RealTime Workshop, then automatically compiled into a VTB model by specifying an icon, etc.

These general properties of the VTB environment support additional capabilities that have high value when solving power quality problems.

II. VTB CAPAB ILITIES FOR SOLVING POWER QUALITY PROBLEMS

The resolution of power quality problems benefits from capabilities that go beyond those available in most network solver environments. Here we describe the specific capabilities of VTB that support the solving of power quality problems, and explain why these capabilities are useful.

Many power system solvers operate on a fixed time step. That is problematic with respect to resolving the time of switching events. The VTB allows variable time steps, which are chosen in a somewhat unique way. Rather than basing the choice of time step on the system eigenvalues, instead any model in the system can request either a) a time at which to end the next step, or b) a rollback of time to the last (valid) time step if an event is triggered that invalidates the current system output (failure to converge, threshold crossing, etc). Both of these capabilities are critical in a simulator for systems that incorporate power electronics in the power quality solution.

Virtually every solution to a power quality problem involves power electronics and every solution to a power electronics problem involves a control system (usually digital). Hence a simulation or virtual prototyping environment for power quality solutions should allow seamless integration of the control design. Most definitely the support for control design must not be an afterthought. The VTB supports control integration through a well-defined and very-complete multistep process.

First, the hardware of the system model is completely defined by using standard components from the VTB model library. The control inputs are left open, awaiting definition of the control model.

The control algorithm is then derived using whatever tools the control engineer prefers. Usually the control design is based on an approximate or perhaps a linearized model of the system, yet the real system is much more complex and contains nonlinearities and signficantly greater detail than would be used in the control design. With the VTB, it is possible to automate the process of system identification without resorting to extensive hand analysis or oversimplification of the system. Rather, the items in the Matlab Control System Toolbox and the System Identification Toolbox can be used to probe the system as it operates in order to “measure” the transfer function or other important quantities. These data can then be used to help formulate the control law.

The next important step is to confirm that the designed control does indeed work when inserted into a high-fidelity model of the system. To do that, the controller is assembled in block diagram form using Simulink.

For initial tests of the Simulink model of the controller, it is convenient to insert the control model into the system as a cosimulation object. This allows the control engineer to interactively refine the controller – the Simulink block diagram and/or the control coefficients can be changed on-line and the effects of those changes on the system dynamics can be directly and immediately observed without ever stopping the simulation.

Once the controller algorithm is designed (plus or minus tolerances on the control parameters), the controller can be compiled into an executable object by using the Realtime Workshop of Matlab in conjunction with VTB’s tool for creating models from compiled Matlab code. The user can specify which parameters should be accessible to the user in the controller dialog box (if any parameters are intended to be user adjustable). The compiled controller model can now be shared with others who may be working on the system design and they do not need to own Matlab/Simulink in order to test how the controller works as modifications or additional detail are added to the system model. At this point, the control design path bifurcates depending on whether or not the designer intends to go directly to an embedded controller or first to a general purpose controller before committing to an embedded controller for production purposes.

If the step through a general purpose controller (such as dSpace) is chosen then the Simulink model can be automatically compiled and downloaded directly to the controller card. Before connecting to real hardware, the particular software implementation of the controller can be tested against the virtual prototype of the system as it runs in

VTB. This we call processor in the loop. Generally this test will NOT detect small timing errors because the system model is stepped slowly, one step after each instruction is executed on the digital control platform.

When the control and system engineers are satisfied that the system has been thoroughly tested the next step can be taken – testing the controller as it is connected to the actual hardware. This test will reveal timing errors if there are any.

Finally, if the power quality solution will be marketed as a commodity device, there is a need to transfer the control algorithm to an inexpensive embedded processor. This step is quite simple if a C-language compiler exists for the processor because the same code that was tested on the general purpose controller (which was the same as the code generated by Simulink) can be compiled for the embedded controller. The embedded controller can again be tested against the VTB system model (processor in the loop) before finally committing the design to production.

III. EXAMPLE APPLICATIONS

To demonstrate the VTB capabilities for solution of typical power quality problems, we use the example of a reconfigurable AC zonal power system and show how the powered equipment in this system can be protected against outages caused by damage to the power distribution infrastructure. Compared to radial distribution, zonal distribution architectures provide maximum protection (fault tolerance), reduced cabling, and cost savings, especially for larger-class ships. Zonal Electric Distribution System use layers of AC-DC, DC-DC, and DC-AC converter modules, which improve system reconfigurability, efficiency, reliability, and survivability. There are additional advantages of Zonal Electric Distribution System, which are listed in some details in reference [1].

A zonal ship power system may consist of AC power generators, transformers, AC and DC power distribution buses, power converter modules, and controllers. The controllers are responsible for advanced power flow control to improve power quality, survivability, and reliability of the ship power distribution network. Interest in using fuel cells as power sources [2] makes the system heavily reliant on power electronics and advanced control strategies to allow seamless integration of various power sources into the system.

Many fault location detection and network reconfiguration techniques for AC power systems are proposed in the literature. Some of the described techniques include application of Artificial Neural Networks (ANN) [3], which have been successfully applied to many power system planning and operation problems in recent years. ANNs are fault tolerant and, once trained, offer relatively short execution times. Some ANN methods have been proposed for fault location detection. Although ANN methods may be well-suited for ground based utility applications, they may not be as efficient in combat ship installations, since proper ANN training would be very difficult to achieve (though a good simulation environment can support that training function). Furthermore, these methods assume that information from the sensors is always available at the control center, which may not always be the case in shipboard power applications. Finally, these systems under some circumstances may generate incorrect diagnoses (9%) or may fail to diagnosis a problem (22%) [3].

Other methods [4] are based on measurements of RMS values of voltages and currents in different locations of the system. The microprocessors installed at each specific location collects information, computes active, and reactive power and other data and sends this information along with information about their location to a higher level computer. Based on this information, the location of a fault can be computed and a command to trip off appropriate breakers is generated. Clearly, implementation of such a system is costly, since it uses many voltage and current sensors, as well as microprocessors. Furthermore, it requires additional communicational infrastructure for information exchange among the microprocessors and main computer. Reliable sensing of RMS values requires at least one cycle (or about 17 msec), therefore system response to any fault cannot be expected in less than 17 msec. In fact, as pointed out in [4], the response time of such systems is about 20 msec, which may not be fast enough for some loads. The very high dependence of this system on informational data channels adversely affects the survivability of such a power protection system in combat ship installations.

Finally, the most advanced and sophisticated techniques employ phasor measurements [5]–[7] to identify fault location. These techniques can identify that a fault has occurred within 0.5 msec and perform coordinated trip off decision for 10 msec [6]. Phasor measurement methods are based on the Clarke transformation and typically are derived from principles of wave propagation in the transmission line [7]. As well-known, voltages and currents in the transmission line are related through the system of partial differential equations:

$$\begin{aligned} \frac{\partial v}{\partial x} &= Ri + L\frac{\partial i}{\partial t} \\ \frac{\partial i}{\partial x} &= Gv + C\frac{\partial v}{\partial t} \end{aligned}, \qquad (1)$$

where v and i are 3×1 vectors of voltages and currents, R, L, G, C are 3×3 matrices of transmission line parameters, and x is a distance from the receiving end.

Under assumption of sinusoidal steady state conditions, equations (1) can be represented in the following form:

$$\begin{aligned} \frac{dV}{dx} &= Z\cdot I \\ \frac{dI}{dx} &= Y\cdot V \end{aligned}. \qquad (2)$$

Clarke transformation is used to de-couple phase quantities and then equation (2) can be solved. Using boundary conditions at fault point and at receiving point, it is possible to derive an expression for fault location index [7].

As it is possible to see from equations (1) or (2), phasor measurement techniques require knowledge of the transmission line parameters. Errors in line parameters estimation can result in significant errors in fault location (20% error in line parameters may result in 6.6% error in fault location [7]). Precise parameters of the lines are not easily obtained. In practice, software tools and subroutines can be used for line parameter adaptive estimation. However, these computations require additional time, which affect overall performance and responsiveness of system.

Additionally, as can be seen, transition from equation (1) to equation (2) implies sinusoidal waveforms for both voltages and currents. This assumption is not always true in a real-life harmonics-rich environment, since many power systems utilize many switching power converters and motor drives that affect power quality. Thus, harmonic distortions would contribute to additional errors in fault location detection. Finally, as it is pointed out in [7], not all types of faults can be detected using phasor measurement techniques.

We propose a new different algorithm for fault location detection and automatic network reconfiguration, if a fault is detected. The algorithm does not pin-point the exact fault location. Instead, it only identifies the zone in which the fault has occurred. Indeed, exact fault location knowledge is not necessary, since breakers and switches are installed at discrete locations and the purpose of the fault detection algorithm is to trip the appropriate switches or breakers off and to re-route the power through alternate unfaulted buses, when a fault is present. As a result of the slightly different objectives described above, the new proposed algorithm is much simpler in implementation and at the same time it has excellent response time and performance. All techniques described above require measurement of voltages and currents (either RMS or instantaneous) at some specific locations. The proposed method utilizes only measurements of instantaneous currents at different locations, thus reducing the cost of the system. The response time of the system is less than 1 msec (compared to 20 msec and 10 msec for other systems). Excellent response time is achieved due to the following reasons: RMS values are not measured; voltage sag is not used for fault detection; intensive computations are not needed to determine exact fault location and for decision search if a fault is detected. The proposed system can work either in autonomous mode or under supervision of a higher level computer or operator. Preliminary studies and simulation results show that the system is not susceptible to relatively high level of harmonic distortions normally present in the power system. Next sections describe the proposed new technique for fault detection and system reconfiguration in some details.

IV. DESCRIPTION OF STUDY SYSTEM

The concept demonstration system is shown in Fig. 2. Figure 3 presents the structure of each zone. A real system can consist of several to many zones connected as shown in Fig. 2.

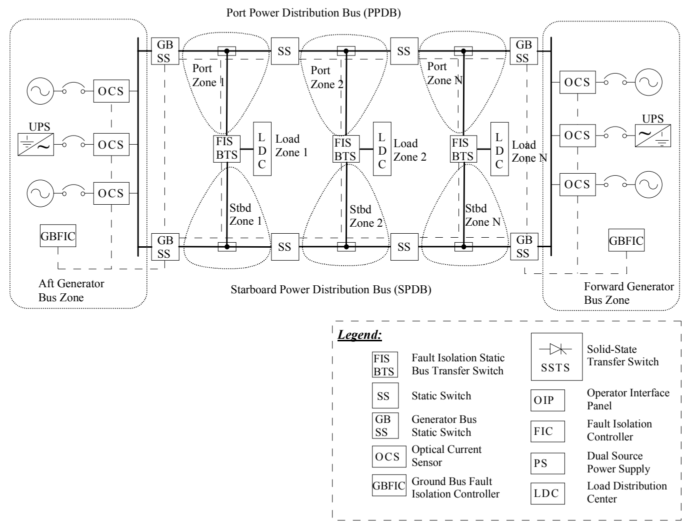

Figure 2. AC Zonal System and Component Diagrams

The zonal system contains Forward and Aft Generators, feeder cables including Port and Starboard Power Distribution Buses, Local Feed and Equipment Power Feed buses, and loads in each zone (LD1, LD2 for Zone 1, and LD3, LD4 for Zone 2). The power distribution system is redundant: in the case of an electrical fault in either the Port or Starboard feeders, the power to the loads is provided by the alternate feeder.

The process of sensing a fault and switching the load to an alternate feed should occur in less than 1ms.

Power is transferred by semiconductor Transfer Switches. Current sensors supply information about state of the system to the Fault Isolation controllers (FIC1 and FIC2), and to the Transfer Switch Controller (TSC). The particular algorithms used to identify the faults are proprietary.

The purpose of each Fault Isolation Controller is to isolate an electrical fault in its own zone only. Thus, FIC1 detects any fault in the Port Feeder cables. As soon as a fault in this zone is detected, the generators are disconnected from the affected cables by controllable switches 1 and 2, and power to the loads (LD1 and LD2) is re-routed by TSC and Transfer Switches through Starboard Feeder cables. When the fault in the Port Feeder is cleared, the Fault Isolation controller can be reset either manually or by a supervisory controller. In the simulation, the controller is reset by sending a logical “1” pulse to the corresponding terminal of the FIC.

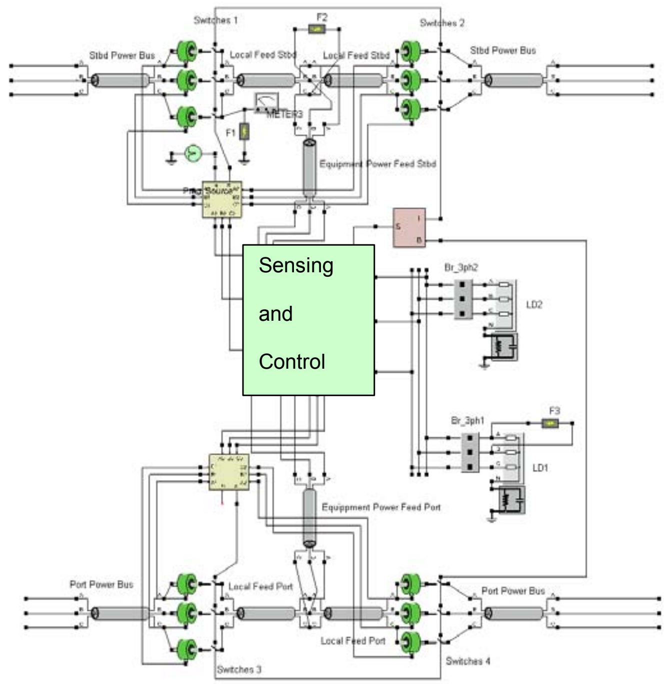

Figure 3. Structure of each Zone, with some details removed to protect proprietary information

The Transfer Switch Controller senses the outputs of the Fault Isolation Controllers, and generates appropriate signals for the Transfer Switches, which connect the loads to the correct feeder cables (Port or Starboard). Feeder priorities can be specified as parameters of the TSC so that either the Port or Starboard Feeder will have priority to supply the power. This provides additional power sharing control when there are no faults in the system. However, if faults are detected in either Port or Starboard Feeders, the power will be transferred to the unfaulted feeder without disturbing sensitive loads.

The proprietary control algorithm has two main advantages. First, by employing instantaneous current sensing, solid state Fault Isolation controllers, and fault isolation switches (Switches 1 and 2) instead of circuit breakers or fuses, the several-cycle fault clearing times characteristic of arc commutation are eliminated. This prevents circulation of high currents, large stresses on power equipment and power outages at the load side. Second, Fault Isolation controllers detect faults only in their corresponding zone. Thus, if a fault has occurred at one of the loads or in another zone, the FIC will not cut all the power from the generators, as would happen using conventional power protection means. Instead, only the faulty equipment or zone will be disconnected, thus improving the survivability and reliability of the overall system. Additional benefits include: elimination of local UPS systems (weight & energy reduction); arc suppression; improved personnel safety (reduce injury and death due to arc blast and electrocution while performing maintenance; no generator trip due to overcurrents during faults.

Finally, it is necessary to point out an important extra benefit. Proposed control strategy is highly flexible and can be used in future DC zonal systems with no or little changes. This makes it attractive for use in current AC installations which may be converted to DC power in the future.

V. Performance of the Study System

The performance of the study system was demonstrated as a virtual prototype in the VTB environment. The scenario begins with power supplied to the loads by the Starboard Feeders (which have the highest priority). At 100 msec a line-to-neutral fault (F1 in the system schematic) of 50 msec duration occurs in Zone 1. Instantly, power is transferred to the Port Feeder cables. Fault F1 is cleared after 50 msec. At 120 msec, when the fault in Zone 1 is not yet cleared, another line-to-neutral fault of 50 msec duration occurs in Zone 2. Power to the loads in Zone 2 is re-routed through the alternative unfaulted cables. During simultaneous faults in both Zones the power flow to all of the loads is not interrupted, and both generators continue to feed all the loads.

At 200 msec the Starboard Fault Isolation Controller of Zone 1 is reset by the external source by a short pulse of logical "1". This transfers the load back to the Starboard feeder. At 300 msec another 50 msec fault, this time line-to-line, occurs in the Staboard Feeder cables of Zone 1. The fault is succesfully detected and power is immediately transferred to the Port Feeder. At 400 msec the top fault isolation controller is reset and the power flows through the Starboard Feeder again. The model of the transfer switch controller allows the user to specify the delay between receiving the command to switch power to another feeder and when the controller actually generates the command. This emulates the time delay in the control circuitry and the behavior of semiconductor devices.

The simulation results are illustrated in Figures 4-19. As can be seen from the distorted waveforms, sources with high harmonics contents (15% to 20% THD) have been used to test protection algorithm performance under severe conditions.

Figures 4 and 5 show phase A currents in the Local Feed Starboard and in the Local Feed Port cables of Zone 1. It is possible to see when the power is transferred from one feeder to another when a fault is detected or when the Fault Isolation Controller receives the “Reset” command. Figures 6 and 7 show phase A currents in the Equipment Power Feed Starboard and in the Equipment Power Feed Port cables of Zone 2. It can be seen when the power is transferred from Starboard feeder to Port cables when a fault is detected.

Figures 8 and 9 present phase A currents of the Forward and Aft Generators and the transients associated with power transfer. Figures 10 and 11 show phase A currents in the loads LD1 and LD2 of Zone 1. As can be seen, the power to the loads is not interrupted by faults or by other power transfers. Finally, figures 12 and 13 present phase A to phase B voltages at the loads LD1 (Zone 1) and LD3 (Zone 2), while figures 14 and 15 show phase A to neutral voltages for the same loads.

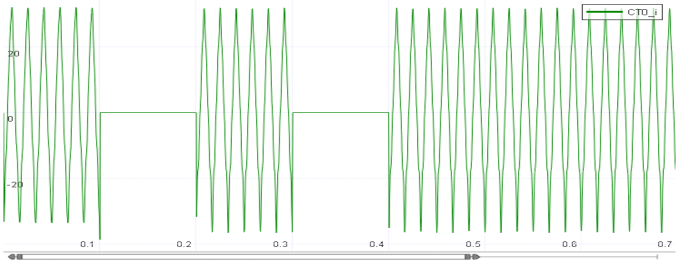

Figure 4. Phase A current through Local Feed Starboard cable of Zone 1

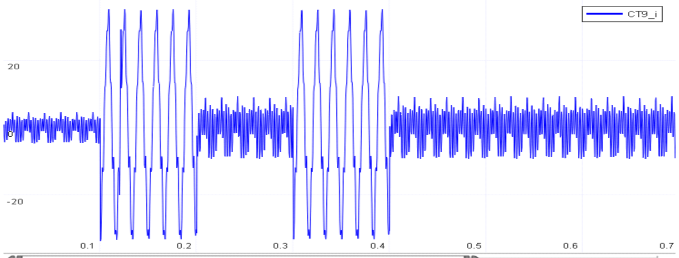

Figure 5. Phase A current through Local Feed Port cable of Zone 1

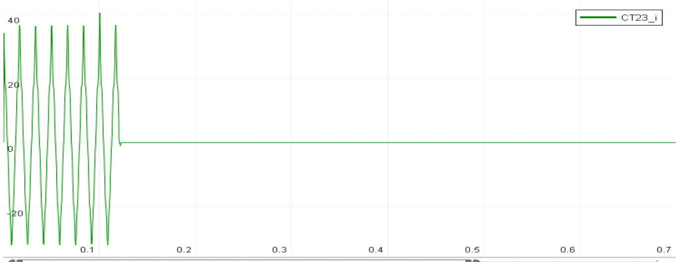

Figure 6. Phase A current through Local Feed Starboard cable of Zone 2

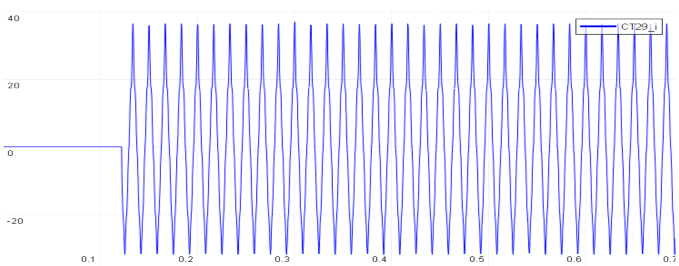

Figure 7. Phase A current through Local Feed Port cable of Zone 2

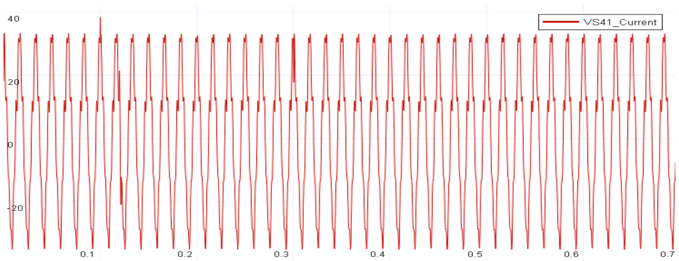

Figure 8. Forward Generator Phase A current

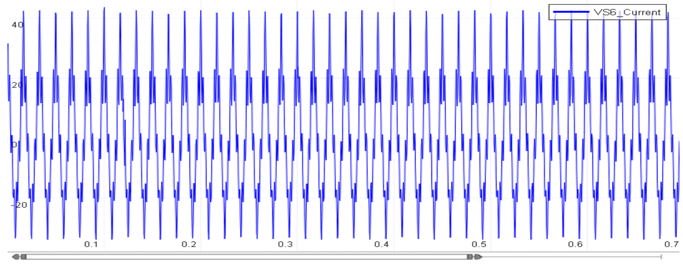

Figure 9. Aft Generator Phase A current

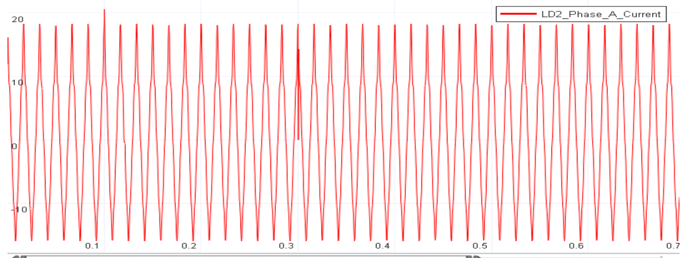

Figure 10. Load LD2 Phase A current

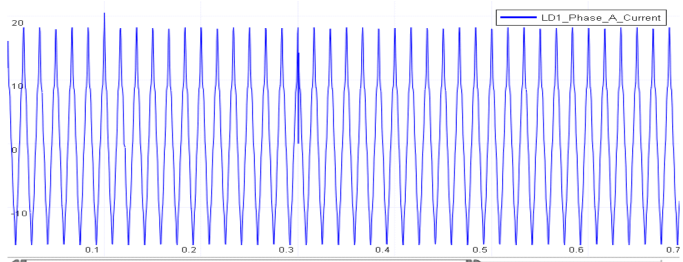

Figure 11. Load LD1 Phase A current

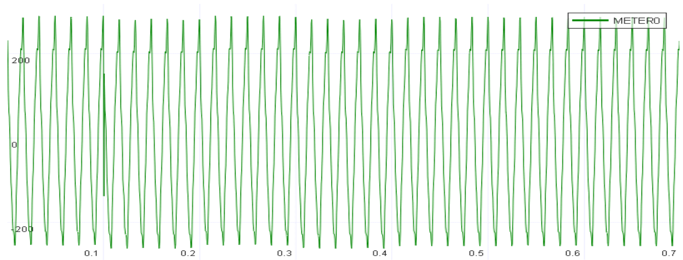

Figure 12. Load LD1 Phase A to Phase B voltage

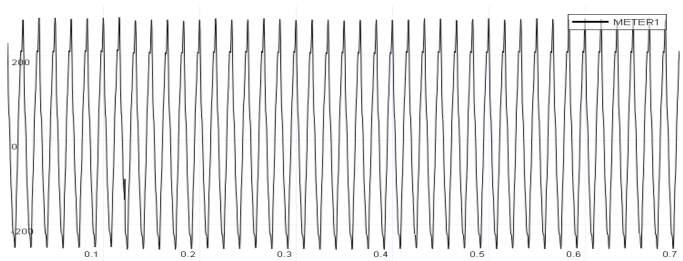

Figure 13. Load LD3 Phase A to Phase B voltage

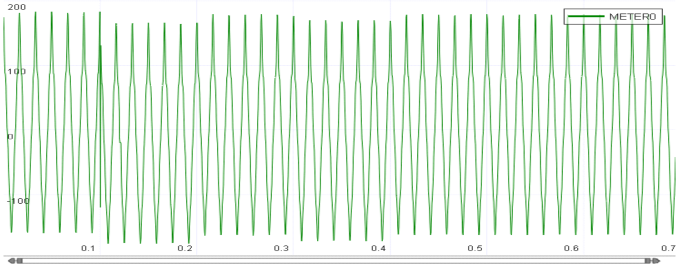

Figure 14. Load LD1 Phase A to neutral voltage

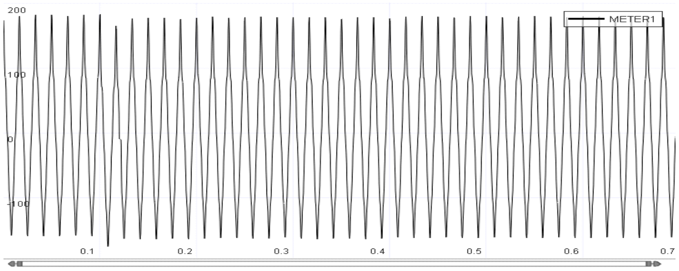

Figure 15. Load LD3 Phase A to neutral voltage

Finally, at 700 msec a fault occurs in one of the loads (LD1) of Zone 1. It takes about a cycle for the corresponding circuit breaker to isolate the load from the power supply. However, none of the Fault Isolation Controllers react to this fault because the fault is not in the distribution system. The phase A load currents (LD 1 and LD2) are shown in figures 16 and 17. Figures 18 and 19 present phase A currents of Forward and Aft Generators during the load LD1 fault.

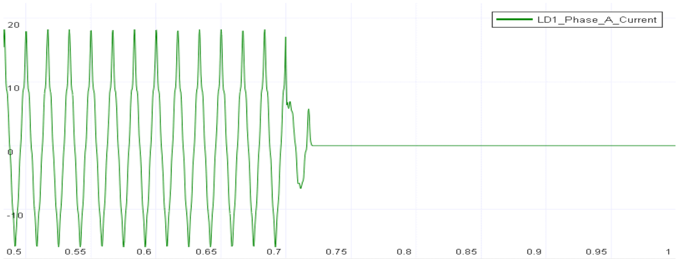

Figure 16. Load LD1 Phase A current during fault

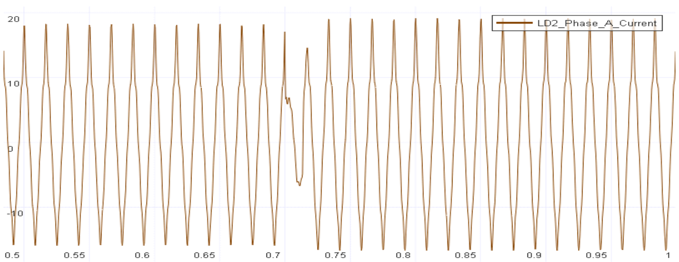

Figure 17. Load LD2 Phase A current during load LD1 fault

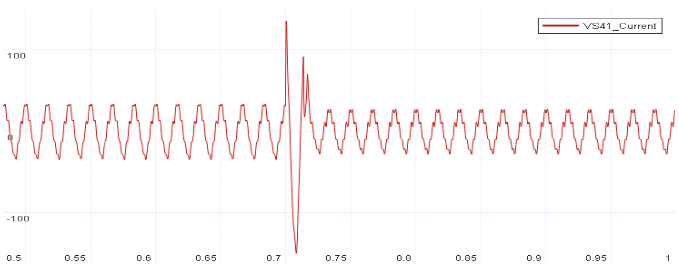

Figure 18. Forward Generator Phase A current during load LD1 fault

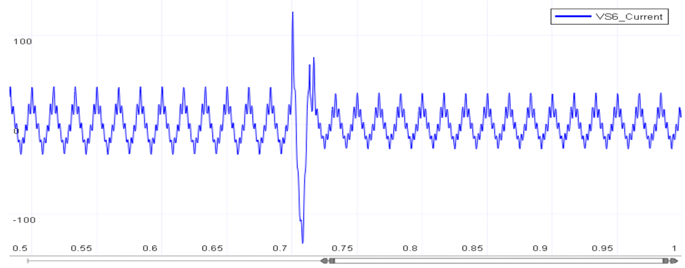

Figure 19. Aft Generator Phase A current during load LD1 fault

A snapshot of the VTB interactive visualization is provided in figure 20. Visualization helps in fast comprehension of the system status at any given time. For example, it can be immediately seen from fig. 20 that system at specific time instant is experiencing fault at Port Power Distribution Bus (PPDB) and that the power to the loads is re-routed through the alternative buses. Status of all system components is color coded and can be easily grasped. For example, green color for breakers tells that breaker conducts while red color indicates that breaker is tripped off. The same color coding is done for transfer and static switches: green color indicates that switch is in conducting mode, while red color alerts that the particular switch is off.

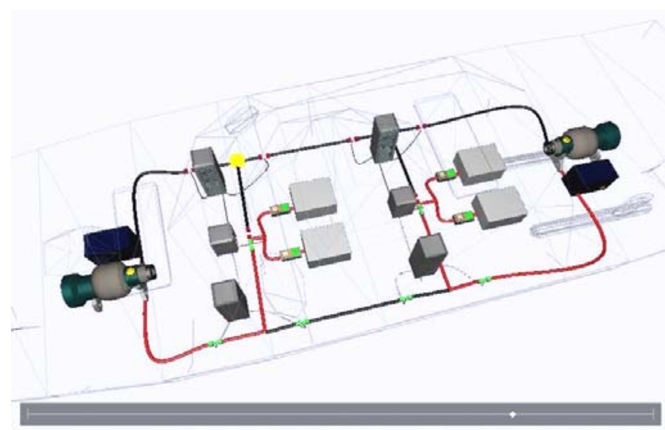
Figure 20. Visualization of the ship's zonal power system

VI. Conclusions

The VTB software is a valuable tool for modeling, simulation, and rapid prototyping of power systems and for solving power quality problems. The VTB interfaces with Matlab/Simulink, Labview, ACSL, Pspice are highly beneficial in many aspects including development, implementation and rapid prototyping of various control algorithms at all levels from low level device controllers to high level system or decision-making controllers. The advanced visualization capability is especially advantageous for comprehending the simulation data.

Simulation results presented in this work show that the proposed AC zonal control algorithm is effective and that it has several important advantages over conventional systems.

Load voltage waveform integrity is maintained throughout all faults. By sensing instantaneous currents in the corresponding zones, the fault isolation controllers react to and isolate faults much faster than conventional means and hence eliminate undesirable secondary effects. The Fault Isolation controllers detect faults only in the corresponding zone, so if a fault occurs in another zone or at a load, the FIC does not break the power flow from the generators as would happen in the case of using conventional (circuit breakers or fuses) power protection means. The Fault Isolation controllers and fault isolation switches eliminate many power quality problems, such as unwanted circulation of high currents in the system, large stresses on power equipment and transient power outages at the load. Instead, only the faulty equipment or zone is disconnected, improving survivability and reliability of the overall system.

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Fast Load Voltage Regulation Using STATCOMs

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***Abstract*-- This paper deals with fast load voltage regulation using a STATCOM. A simplified system representation in a *dq* frame synchronized with the load voltage is used to explain the basis of instantaneous shunt reactive compensation for effecting voltage regulation. Considerations for controller design in terms of bandwidth issues are outlined. Finally, a preliminary controller is designed and simulation results showing its efficacy are presented.**

***Index Terms*—STATCOM control, reactive compensation, flicker control, load voltage regulation.**

I. Introduction

TIME varying loads such as electric arc furnaces [1], and fluctuating output power of wind generation systems [2] lead to the problem of voltage flicker. Voltage flicker may be thought of as an amplitude modulation process with the voltage magnitude varied in a frequency range from 0.5 to 30 Hz [9]. The magnitude of variations is usually less than 10% and is not important for most household appliances. However, its effect on incandescent lamps causing continuous variation in luminosity is disconcerting to the human eye. In particular, the human eye is extremely sensitive to modulations in the frequency range of 5 Hz to 20 Hz [1]. Reactive power compensation has been suggested and is being used for flicker mitigation. Thyristor based Static VAR Compensators (SVCs) are traditionally used for this purpose [1]. However, these are limited in their control bandwidth and therefore not effective for compensating higher frequency modulations. For higher bandwidth shunt connected Static Compensators (STATCOMs), and series active filters, both based on pulse width modulated converters have been proposed [1]-[3], [5], [9]. This paper concentrates on STATCOMs for voltage flicker compensation. For effecting fast control, the STATCOM is usually modeled using the *dq* axis theory for balanced three-phase systems [4]. This allows definition of instantaneous reactive current injected by the STATCOM. This is important since energy storage or real power capability is not available in STATCOM. The other important feature of this approach is that the system quantities appear as DC in steady state. Methods have also been proposed for unbalanced system conditions, albeit with bandwidth limitations, like the single-phase *dq0* transform in [5].

Most of the literature on STATCOM control concentrates on control of output current and dc bus voltage for given a reactive current reference. Regulation of the load voltage is achieved using a PID controller that generates the reactive current reference. To the author's knowledge, a standard procedure for obtaining the PID parameters based on the system parameters is not available. In addition, it is usually assumed that the instantaneous frequency of the load voltage is constant and equal to the line frequency of the infinite bus. This paper treats the above mentioned issues in some detail with reference to a very simple system model.

Section II describes the representation of the system in a *dq* frame synchronized with the load voltage necessary for fast control of the load voltage magnitude. Section III outlines the considerations for controller design with regard to dynamic compensation, and includes a preliminary controller and associated simulation results.

II. System Model

A. System Description

The system model used here is a simplified version of an actual system consisting of a load supplied on a distribution system. One phase of the model is shown in Fig. 1(a). It consists of the source modeled as an infinite bus with purely inductive source impedance, a load modeled by a resistance, and the STATCOM modeled as a controllable current source. Balanced three phase conditions are assumed and the STATCOM current dynamics are neglected. The following equation describes the dynamics associated with the three phases:

$$L_s \frac{di_{s,abc}}{dt} = -R_L \cdot i_{s,abc} - R_L \cdot i_{SC,abc} + v_{s,abc} \qquad (1)$$

Here, $i_{s,abc}$, $i_{SC,abc}$, and $v_{s,abc}$ are vectors consisting of the individual phase quantities denoted in Fig. 1(a), R_L is the

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load resistance, and L_s is the source inductance. Under the assumption that zero sequence components are not present, the system can be transformed to an equivalent two phase system by applying the following three to two phase transformation to all the variables.

$$v_{s,\alpha\beta} = v_{sa} \cdot e^{j0} + v_{sb} \cdot e^{j2\pi/3} + v_{sc} \cdot e^{j4\pi/3} \quad (2)$$

where the complex number $v_{s,\alpha\beta} = v_{s\alpha} + j \cdot v_{s\beta}$.

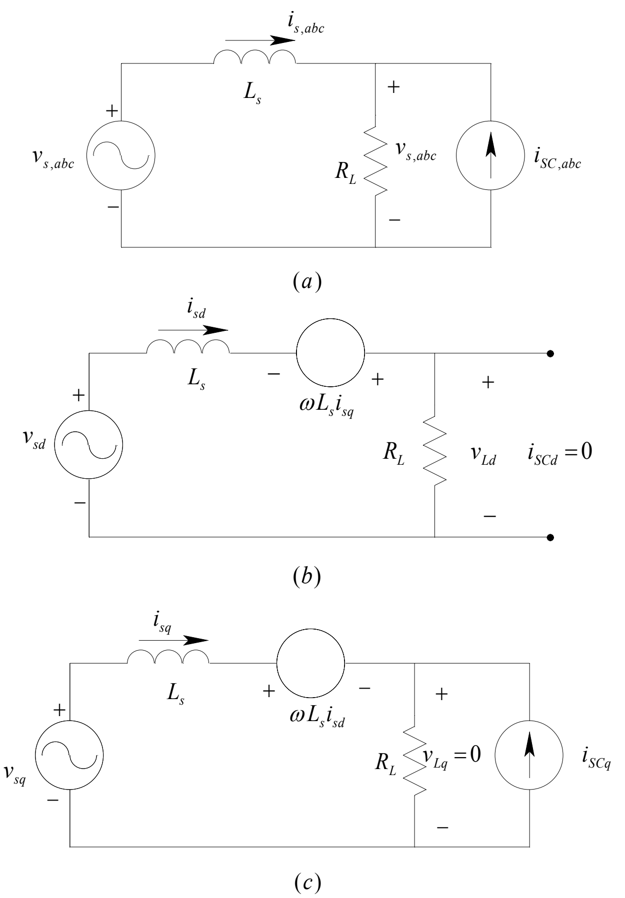

Fig. 1 (a) One phase of the system model; (b) d-axis equivalent circuit; (c) q-axis equivalent circuit.

This is followed by the rotational transformation:

$$v_{s,dq} = v_{sd} + j \cdot v_{sq} = e^{-j\theta} \cdot v_{s,\alpha\beta} \quad (3)$$

where θ is obtained as:

$$\theta = \tan^{-1}\left(v_{s\beta} / v_{s\alpha}\right) \quad (4)$$

Applying the two transformations, (1) can be written as

$$L_s \frac{di_{s,dq}}{dt} = -(R_L + j\omega L_s) \cdot i_{s,dq} - R_L \cdot i_{SC,dq} + v_{s,dq} \quad (5)$$

where ω, a function of time, is given by $\omega = d\theta / dt$ and equals the line frequency in steady state. The equivalent circuits corresponding to the real (*d*-axis) and imaginary (*q*-axis) components of this equation are shown in Fig. 1(b) and 1(c) respectively. If negative sequence components are not present then the variables in (5) are dc quantities in steady state.

B. Remarks About System Representation

Under the condition that the STATCOM supplies only reactive power, so that $i_{SCd} = 0$, the real part of (5) is given by

$$L_s \frac{di_{sd}}{dt} = -R_L i_{sd} + \omega L_s i_{sq} + v_{sd} \quad (6)$$

In addition, definition of θ using (4) ensures $v_{Lq} = 0$ so that v_{Ld} represents the instantaneous magnitude of the phase voltages $v_{L,abc}$. Thus,

$$v_{Ld} = R_L i_{sd} \quad (7)$$

and

$$i_{sq} = -i_{SCq} \quad (8)$$

Eqn. (8) is a consequence of the assumption that the STATCOM current dynamics can be neglected. Thus, for this system i_{sq} cannot be considered an independent state. In a real system, the STATCOM would be coupled to the grid with a capacitor across the load, and the i_{SCq} dynamics will also involve power system parameters corresponding to the source impedance and v_{sq}, the *q*-axis component of the source voltage. Effect of power system parameters on the STATCOM current loop dynamics was studied to some extent in [6]. It was stated that since the power system parameters can vary over a wide range the current control loop design should be robust to the expected variations. Such effects have not been considered here but will be the subject of further investigation. Utilizing (8), (6) can be written as

$$L_s \frac{di_{sd}}{dt} = -R_L i_{sd} - \omega L_s i_{SCq} + v_{sd} \quad (9)$$

Further, (7) and (9) lead to the load voltage equation

$$\frac{dv_{Ld}}{dt} = -\frac{R_L}{L_s} v_{Ld} - R_L \omega i_{SCq} + \frac{R_L}{L_s} v_{sd} \quad (10)$$

III. Controller Design for Load Voltage Regulation

A. Instantaneous Reactive Compensation for Load Voltage Regulation

The basic idea of reactive compensation for voltage regulation comes from sinusoidal steady state. However, from (10) it is evident that regulation can be effected under dynamic conditions as well. A negative value of i_{SCq} (capacitive compensation) leads to an increase in the load voltage. From (9) it is clear that a negative i_{SCq} causes an increase in real power transfer from the source under dynamic conditions. This is to be expected since the increase in real power consumed by the load cannot be supplied by the STATCOM. An increase in reactive power demand of the load can on the other hand be theoretically compensated.

The particular rotation angle θ chosen for the stationary to rotational frame implies that the regulation of the phase voltage magnitudes under dynamic conditions is the same as regulation of v_{Ld}. In much of the published literature (e.g. [1]) the angle θ (or equivalently $\cos\theta$ and $\sin\theta$) needed for the transformation (3) is derived from the line voltage by means of a Phase Locked Loop (PLL). A PLL would necessarily ignore high frequency transients. In [7] the PLL delay is quoted to be more than half a line cycle. In [7] it is also stated that there exists a coupling between i_{SCq} and v_{Lq} due to the line resistance. However, it is not clear why v_{Lq} should not be zero if (4) is used to define θ. To keep this coupling low enough, the voltage regulation bandwidth was limited in [7]. This prevents power system oscillations. As explained in Section I, a STATCOM can regulate voltage by either by supplying reactive power or by effecting a real power transfer from the source. Thus, real power oscillation in the amount necessary to compensate time varying loads or fluctuating generated power is a must unless some energy storage is available. Energy storage for voltage regulation in the presence of fluctuating real power demand has been addressed to some extent in [1].

B. Design of Voltage Control loop: Methods and Dynamic Response Issues

Usually PID controllers are used for the load voltage loop. The voltage magnitude error is the input and the *q*-axis STATCOM current reference is the output that goes to the STATCOM current controller. A method for deriving the small signal transfer function of the change in load voltage with change in i_{SCq} needed for this approach is described in [10]. However, the application considered there is voltage sags, a slower phenomena compared to voltage flicker, and an assumption is made that ω is constant and equal to the source frequency. Other than experimental procedures like Zeigler and Nichols [8], to the author's knowledge, there is no standard procedure for choosing PID parameters to ensure sufficient bandwidth for flicker compensation and robustness to system variations. Due to the time varying nature of ω equation (10) is non-linear. If the gains are chosen low enough then the variation in $v_{L,abc}$ would be slow and the assumption that ω is constant and equal to the line frequency ω_s would be valid. Clearly, this is not true if a faster response is desired.

The problem of voltage regulation using the *dq* axis construct may be compared to a certain extent with Rotor Field Oriented Control (RFOC) in Induction Motors (IMs) [11]. The angle used for stationary to rotational frame transformation used in RFOC depends on the slip speed. The slip speed in turn depends on the torque reference, which is proportional to the *q*-axis component of the stator current. No assumption about rate of change of ω is necessary, and only the leakage inductance and the available inverter voltage restrict the current controller bandwidth. In case of STATCOM, load voltage magnitude is controlled by i_{SCq}, and changes i_{SCq} also affect the angle θ.

C. Preliminary Controller Design and Simulation Results

If the desired constant voltage magnitude corresponds to $v_{Ld}*$, (10) can be rewritten in terms of the error, $e = v_{Ld}* - v_{Ld}$

$$\frac{de}{dt} = -\frac{dv_{Ld}}{dt} = -\frac{R_L}{L_s}e + R_L\omega i_{SCq} - \frac{R_L}{L_s}\left(v_{sd} - v_{Ld}*\right) \quad (11)$$

Thus the current command $i_{SCq} = \frac{1}{\omega L_s}(v_{sd} - v_{Ld}*)$ ensures exponential decay of the error with time constant L_s / R_L. Additional damping may be added by subtracting terms proportional to e/ω from the current i_{SCq}. This controller implicitly assumes knowledge of the power system parameters v_{sd} and L_s, and that ω can be measured or estimated.

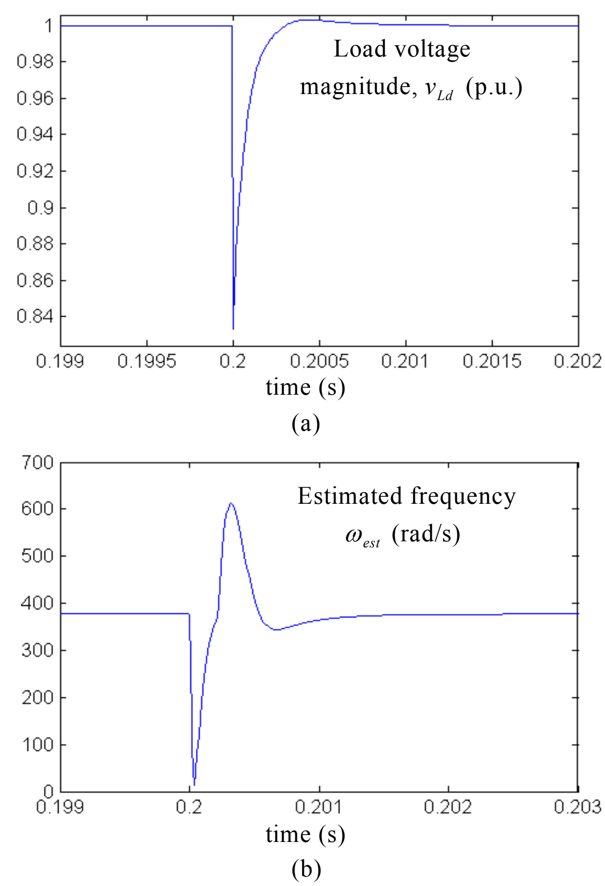

Fig. 2 Step Response: (a) Load voltage; (b) estimated frequency.

The system was simulated in SIMULINK with the electrical circuit modeled by means of the Power System Blackest. Parameters used were taken from the laboratory prototype used in [6]. The load was made completely resistive. Specifically,

R_L	2.85 Ohm
L_s	0.17 mH
V_s	110 V rms (1 p.u.)

A step change in load, 100% to 120%, was applied by parallel connection of resistors. Step response for the voltage magnitude is shown in Fig. 2(a). Fig. 2(b) shows the estimated instantaneous frequency, ω. As expected, ω deviates considerably from the line frequency ω_s during the transient. Next, a three-phase balanced current source of magnitude equal to the load current and frequency of 20Hz was connected in parallel with the load. This simulates the effect of pulsating load power. Fig. 3(a) and 3(b) show the phase *a* voltage waveform without and with compensation respectively. The '*' symbols indicate the peaks of the voltage waveform. As seen, oscillations in the voltage magnitude are attenuated substantially. At this point, the controller design is in a preliminary stage and needs further study with respect to disturbance rejection.

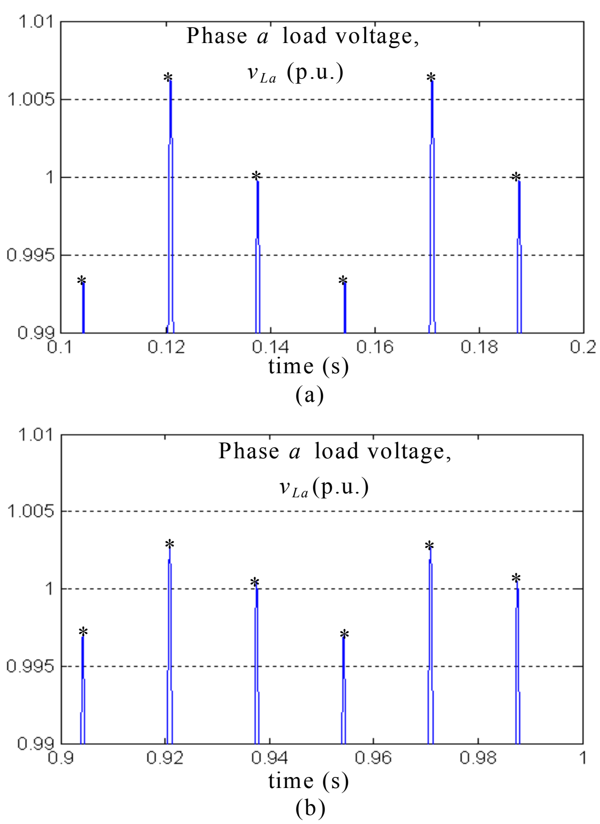

Fig. 3 Voltage magnitude variation: (a) without compensation; (b) with compensation.

IV. Summary

This paper has given a brief overview of fast load voltage regulation using a STATCOM. Using a simplified system representation, the basis of instantaneous reactive compensation for effecting voltage regulation has been explained. Considerations for controller design have been outlined. A preliminary controller has been designed and corresponding simulation results showing its efficacy have been presented. Work on this problem is still in progress and the following issues are being addressed further:

- Modeling of a system without some of the assumptions made here.
- Comprehensive design of the STATCOM control for output current, the dc bus voltage, and load voltage. Emphasis is on the coupling between the STATCOM and a typical distribution system.
- On-line estimation of power system parameters for controller design.

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Power Electronics and Power Quality - Problems, Analysis, Solutions and Opportunities

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Abstract - This presentation attempts to give an overview of the impact of power electronic loads on power quality through a snap shot of relevant research activities at the Center for Power Electronics Systems (CPES) and elsewhere. It is well known that power electronic loads can cause various power qualities issues, such as harmonics, inrush, imbalance, and high frequency noise. Examples will be presented to illustrate these phenomena associated with power electronic loads. Analysis tools used to study power quality issues with power electronics will be described with emphasis on CPES research of the average modeling techniques and EMI modeling. Selected solutions to the power quality problems will be presented, including multi-pulsing techniques, noise controlling techniques through packaging and dv/dt control, common mode voltage elimination, and increasing switching frequencies. Power electronics also offer some exciting opportunities for improving system power qualities. Power converters can be used for filtering, dynamic voltage/current compensator, and interface for UPS and other types of energy sources including distributed energy resources. CPES researches on modular plug and play power electronics building blocks will be introduced for these applications.