A Low-Cost Modulated Filter Compensator for Energy-Efficient Enhancement in AC Utilization Systems

Adel M. Sharaf, *Senior Member, IEEE*, Yevgen Biletskiy, *Member, IEEE*, and Hassan A. Mahasneh, *Student Member, IEEE*

***Abstract*—The paper presents a low cost FACTS-based self adjusting power filter and capacitor compensation scheme (PF-CC). The topology and switching strategy of this scheme (developed by the first author) is controlled by self adjusting dynamic tri-loop error driver regulator. The FACTS-based compensation device is necessary in low voltage (below 1KV) residential, commercial and small industrial loads with a substantial mixture of nonlinear arc, converter, and temporal inrush motorized loads. The proposed low cost scheme can ensure voltage stabilization, power quality enhancement, efficient utilization, and self switching and voltage flicker control. Nonlinear and temporal inrush motorized loads are mushrooming in use especially in consumer electronics, commercial and small industrial applications.**

***Key words*—Low-Voltage, Dynamic FACTS, Dual Filter, Capacitor Compensators, Self Adjusting Power Filters.**

I. INTRODUCTION

Harmonics, voltage sag/swell and persistent quasi-steady state harmonics and switching excursion can result in equipment failure, malfunctions, hot neutral, ground potential use, and fire and shock hazards in addition to a poor power factor and inefficient utilization of electric energy. Such inefficient utilization is manifested in increase reactive power supply to the hybrid load, poor power factor and severely distorted voltage and current waveforms.

Nonlinear industrial/commercial schemes are now mushrooming as they represent a composite load family comprising lightning, motorized, computers, arc type, and low power factor industrial processes, such as rectifiers, power supplies and inrush type loads. Such composite load often cause voltage flicking, power quality quasi-static waveform distortion and harmonic interference, which in turn cause automatic data processing component failure and computer data.

The nonlinear volt-ampere characteristics are introduced by analogue or switching type nonlinearity results in dynamic, quasi-static harmonics and inter-harmonics. Harmonics can propagate through the AC utilization/distribution system causing multiple problems and power quality concerns [1]. The use of fixed power filters and LC compensators may not be adequate for quasi-dynamic harmonics generated by nonlinear load switching devices; hence, the need for a new adaptable power filter/compensator is obvious.

Electric utility power quality (PQ) problems are classified as any abnormal occurrence manifested in voltage/current waveforms, or frequency deviations that results in supply failure or any mis-operation of an electronic equipment [2, 3, 4]. It is a growing concern for electric utilities, equipment manufacturers and major electricity users. Utilities have a shared responsibility in addressing and solving these PQ problems. Power Quality problems are increasing due to world-wide proliferation of nonlinear loads and increasing use of sensitive power electronic equipment in process control and automation. Voltage sags, swells, and momentary power supply interruptions are also persistent problems in large electric power grid systems. These shortfalls in supply power quality can be very expensive in terms of sensitive industrial process shutdowns as well as electronic equipment malfunctions. Generally speaking, there are three fundamental changes in the nature of customer loads and power systems which drive the engineering PQ problems and concerns [5, 6, 7].

Harmonics and PQ problems [8, 9] are byproducts of solid state converters, industrial rectifiers, switching mode power supplies and arc type load such as lightning and arc furnaces. Electric utility supply PQ problems including harmonics, dynamic and quasi-static waveform distortion are now top priority issue for equipment manufactures, users, and electric utilities. Nonlinear loads are causing dynamic, quasi-static and transient type harmonics of integral, sub-, super- and inter harmonic content. Other non-integer modulating type frequency signals are introduced by load nonlinearities. These peculiar frequencies are generated by periodic and temporal load variations along with the nonlinearity in the load, whether analogue or switching-type nonlinearity. Voltage drop calculations, reactive power compensations and power factor correction become complex issues in presence of three non-common, non-sinusoidal feeder voltage and current waveforms [10].

The use of fixed, discrete or switched capacitor banks alone may not be effective in enhancing power factor and ensure reactive load compensation. Capacitors for power factor correction may not be adequate with the new type of residual and distortion reactive currents associated with non-sinusoidal load behavior; hence, they are requiring new power definition [11, 12]. The problem is also complicated because of spurious “stochastically” generated and randomly varied uncommon voltage and current harmonics.

All authors are with Department of Electrical Engineering, University of New Brunswick, Fredericton, New Brunswick, E3B 5A3
E-mail: {sharaf, biletski, H.Mahasneh} @unb.ca

II. DIGITAL SIMULATION RESULTS

Fig. 1 depicts the novel pulse width modulated power filter and capacitor compensator (MPF-CC) developed by the first author. Fig. 2 shows the structure of the dynamic multi-loop error driven controller adjusting the pulsing sequence to ensure the combined load bus voltage stabilization, PQ, enhancement and reduce harmonic content due to load switching excursions.

The sample study system shown in Fig. 1 was digitally simulated without and with the developed by First Author dual MPF-CC filter, which is a member of a family of green plugs, switched/modulated power filters and flexible LC compensators [13, 17], used for power quality voltage regulation, energy savings, and reactive compensation.

The details of the sample study system, nonlinear load and control parameters are given in Appendix. The sample three phase form wire study system was tested in load excursions and phase balanced as well as unbalanced linear and nonlinear operation. Fig. 3 and Fig. 4 show the dynamic response of the sample study system without and with the dual power filter compensator. The total harmonic distortion (THD) in voltage and current waveforms at both input (source) and output (load) lines are evaluated without and with the dual power filter compensator with the add on neutral current trap (NCT). The neutral return current and neutral voltage were also evaluated to ensure safe neutral and avoid hot ground short and ground potential rise GPR. Table 1 summarizes the effective filtering action and reduction in GPR levels.

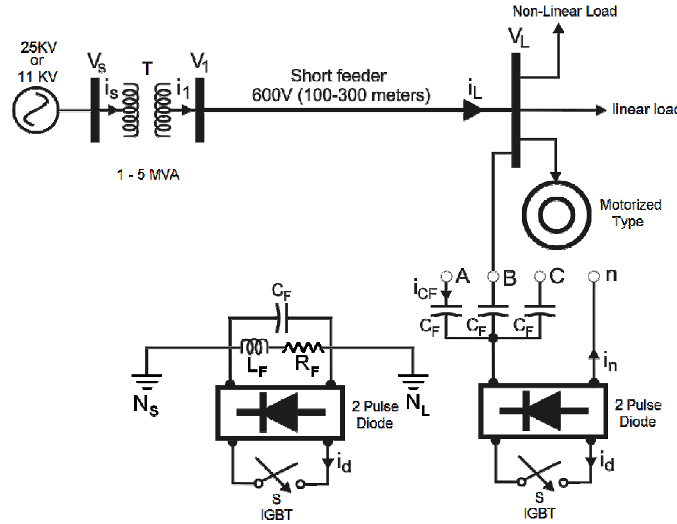


Fig.1. Sample study system with proposed novel MPF-CC dual filter/Compensator scheme and neutral current trap (NCT).

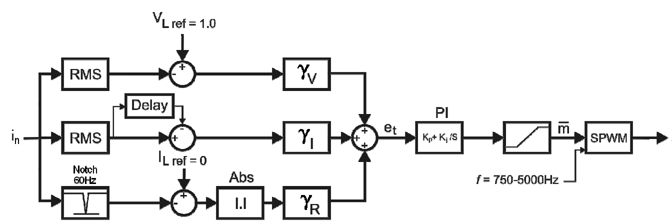


Fig. 2. Tri-loop dinamic error driven (PI) control scheme for sinusoidal pulse width modulation (SPWM)

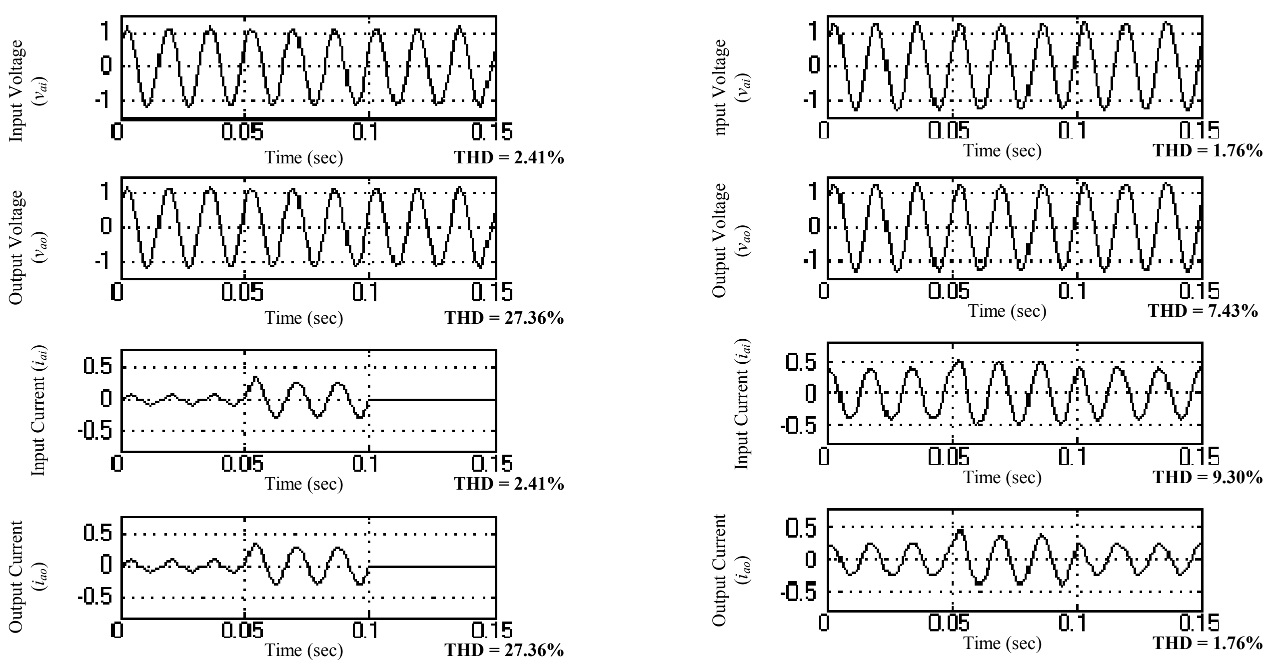
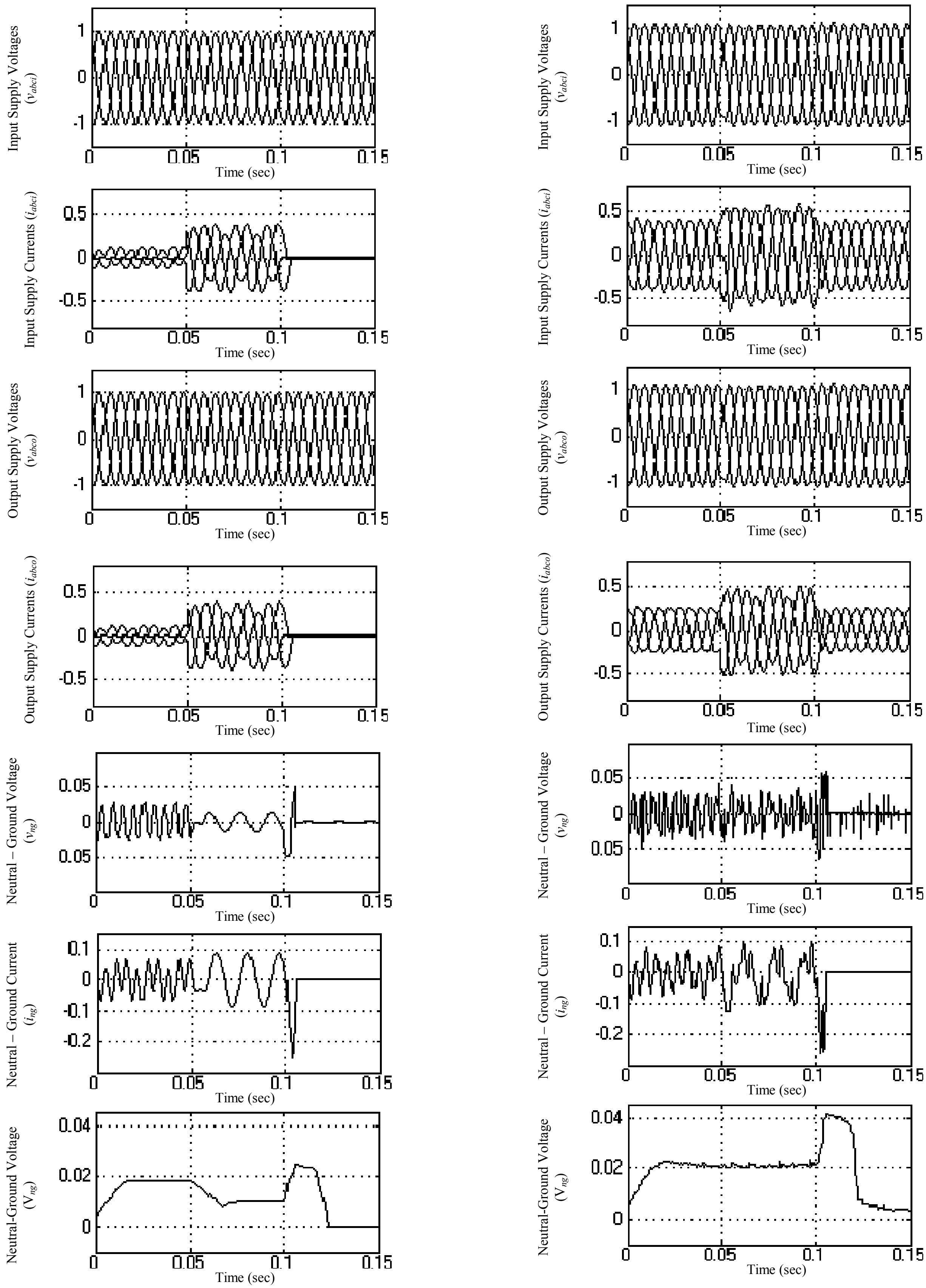


Fig. 3. Comparison of waveforms without and with the dual power filter compensator


Input Supply Voltages (v_{abci})
Time (sec)
Input Supply Currents (i_{abci})
Time (sec)
Output Supply Voltages (v_{abco})
Time (sec)
Output Supply Currents (i_{abco})
Time (sec)
Neutral – Ground Voltage (v_{ng})
Time (sec)
Neutral – Ground Current (i_{ng})
Time (sec)
Neutral-Ground Voltage (V_{ng})
Time (sec)
Input Supply Voltages (v_{abci})
Time (sec)
Input Supply Currents (i_{abci})
Time (sec)
Output Supply Voltages (v_{abco})
Time (sec)
Output Supply Currents (i_{abco})
Time (sec)
Neutral – Ground Voltage (v_{ng})
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Neutral-Ground Voltage (V_{ng})
Time (sec)

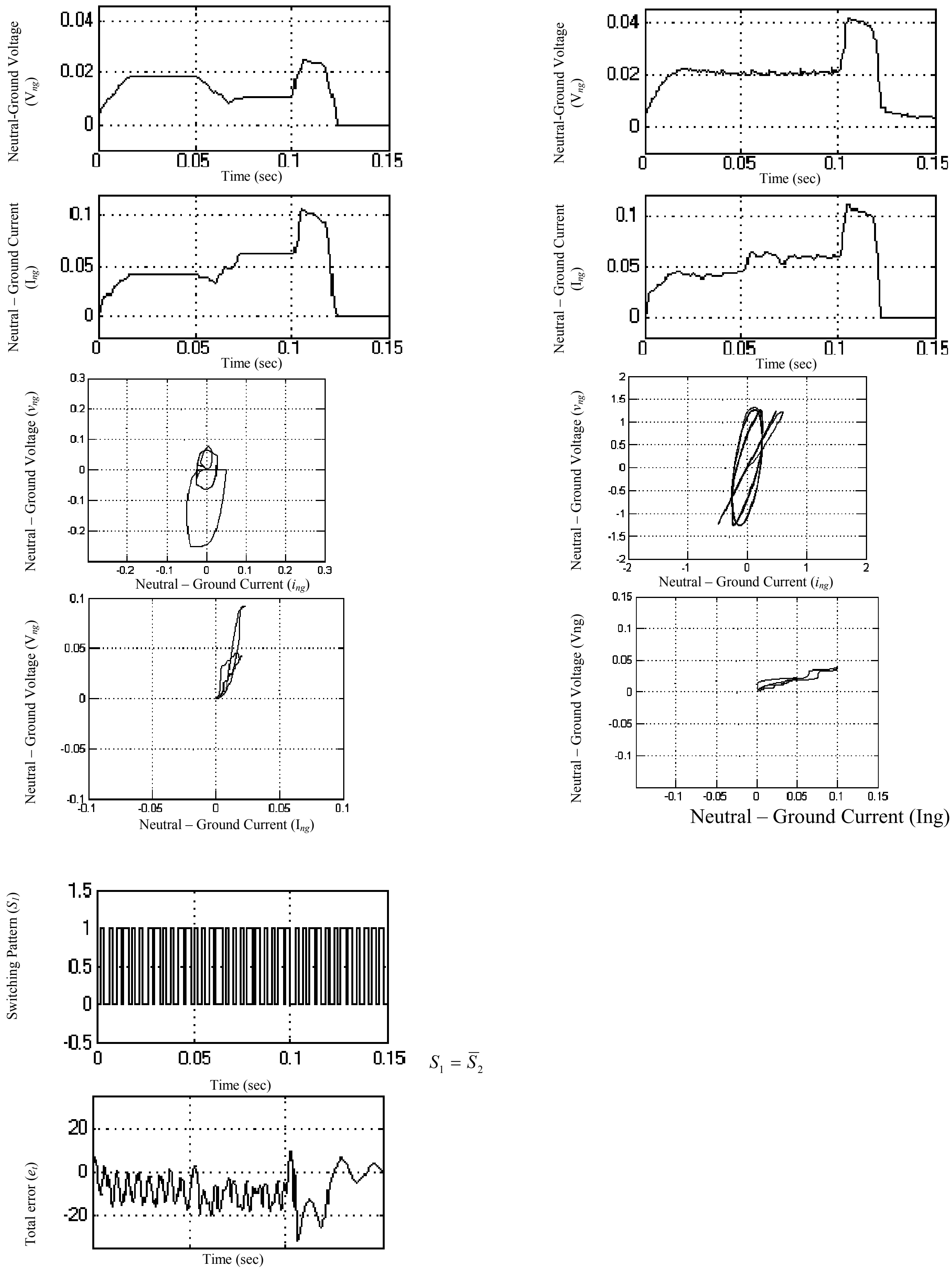


Fig. 4. Comparison of waveforms without and with the dual power filter compensator (continued)

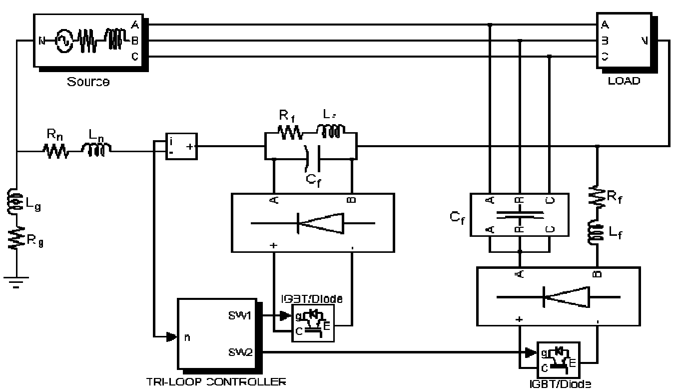
III. Conclusions

The paper presented the development and validation of a novel dual FACTS-modulated power filter and capacitor compensator device (MPF-CC). For dynamic load voltage stabilization, power quality enhancement and efficient utilization using a dynamic tri-loop on-line error driven control scheme. The MPF-CC FACTS device has been validated using the MATLAB/Simulink SIMPOWER software.

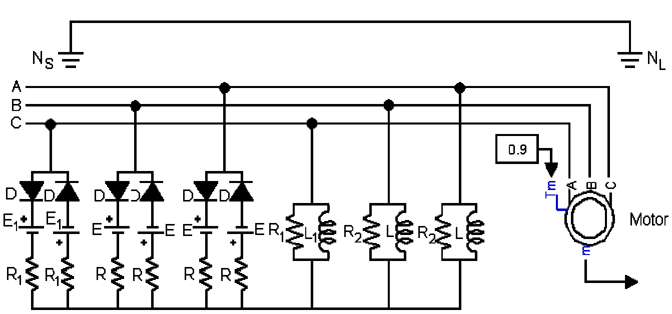
The paper presented digital validation study of the proposed scheme in the low voltage 600V, 3-pahse 4-wire utilization system shown in Fig. 1. The dual modulated power filter and switched capacitor compensator MPF-CC is effective in load bus RMS voltage stabilization improving power quality enhanced AC supply power-factor and reducing harmonics and waveform distortion. The dual power filter and compensator were validated for a sequence of load excursions and disturbances as well as different types of nonlinear loads representations including arc, converter, temporal and on-off inrush type electric loads. The selection of the dual filter neutral return impedance is dependent on the dominant nonlinear load type.

IV. Appendix

AC System and Feeder parameters:
- 2-Pulse Diode Rectifier Bridge;
- C_f= 250μF, L_f= 10mH, R_f= 10Ω;
- Two IGBT/Diode switches; R_{on}= 0.001, R_S= 100000, C_S = inf.



Hybrid Loads (Linear, Non-linear, and Motorized Loads):
- Unbalanced Non-Linear Load R_1 = 24, R = 20, E = E_1 = 200V;
- Unbalanced Linear Load $|X_{L1}|$ = 12; $|X_{L2}|$ = 10;
- Balanced Motorized Load Power 60KVA, V_{LL} = 600$V_{rms.}$



Tri-loop dynamic controller parameters:
- The gains: K_P = 100, K_i = 10, (K_P/K_i = 0.1), Delay time = 10ms, Notch filter at 600Hz; γ_V = 1, γ_I = γ_R = 0.5;
- SPWM: Carrier Frequency = 750Hz, Modulation Index = 0.6.

The switching load excursion was modeled as:
- Linear load from t = 0 to t = 0.05 sec;
- Nonlinear load from t = 0.05 to t = 0.1 sec;
- Motorized load from t = 0.1 to t = 0.15 sec.

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