International Research Journal of Advanced Engineering and Science
ISSN: 2455-9024

A Novel Reduced Switch Power Quality Improvement for Current Harmonic Compensation and Voltage Sag Mitigation Using Model Predictive Control

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***Abstract*— *Power quality is one of major concerns in the present area. It has become important, especially, with the introduction of sophisticated devices, whose performance is very sensitive to the quality of power supply that results in a failure of end use equipment's. One of the major problems dealt here is the voltage sag. To solve this problem, custom power devices are used. One of those devices is the Dynamic Voltage Restorer (UPQC), which is the most efficient and effective modern custom power device used in power distribution networks. Its appeal includes lower cost, smaller size, and its fast dynamic response to the disturbance. It can provide the most commercial solution to mitigation voltage sag by injecting voltage as well as power into the system. This paper presents modeling, analysis and simulation of a (UPQC) using MATLAB and to verify the results of hardware implementation. The efficiency of the UPQC depends on the performance of the efficiency control technique involved in switching the inverters. In this model a Model predictive control and Scalar PWM pulse generator was used.*

***Keywords*— *Unified power quality conditioner (UPQC), power quality, voltage sag.*

I. INTRODUCTION

Modern electric power systems are complex networks with hundreds of generating stations and thousands of load centers are interconnected through long power transmission and distribution networks. Power quality is major concern in industries today because of enormous losses in energy and money. With the advent of myriad sophisticated electrical and electronic equipment, such as computers, programmable logic controllers and variable speed drives which are very sensitive to disturbances and non-linear loads at distribution systems produces many power quality problems like voltage sags, swells and harmonics and the purity of sine Waveform is lost. Voltage sags are considered to be one of the most severe disturbances to the industrial equipment's.

Power quality problems are associated with an extensive number of electromagnetic phenomena in power systems with broad ranges of time frames such as long duration variations, short duration variations and other disturbances. Short duration variations are mainly caused by either fault conditions or energization of large loads that require high starting currents. Depending on the electrical distance related to impedance type of grounding and connection of transformers between the faulted/load location and the node, there can be a temporary loss of voltage or temporary voltage reduction (sag) or voltage rise (swell) at different nodes of the system.

Power distribution systems, ideally, should provide their customer with an uninterrupted power flow at smooth sinusoidal voltage at the contracted magnitude level and frequency .A momentary disturbance for sensitive electronic devices causes voltage reduction at load end leading to frequency deviations which results in interrupted power flow, scrambled data, unexpected plant shutdowns and equipment failure. Voltage lift up at a load can be achieved by reactive power injection at the load point of common coupling (PCC). The common method for this is to install mechanically switched shunt capacitors in the primary terminal of the distribution transformer. The mechanical switching may be on a schedule, via signals from a supervisory control and data acquisition (SCADA) system, with some timing schedule, or with no switching at all. The disadvantage is that, high speed transients cannot be compensated. Some sag is not corrected within the limited time frame of mechanical switching devices. Transformer taps may be used, but tap changing under load is costly.

Another power electronic solution to the voltage regulation is the use of a dynamic voltage restorer (UPQC). UPQC's are a class of custom power devices for providing reliable distribution power quality. They employ a series of voltage boost technology using solid state switches for compensating voltage sags/swells. The UPQC applications are mainly for sensitive loads that may be drastically affected by fluctuations in system voltage.

II. METHODOLOGY

Model Predictive Control

Model Predictive Control is the only advanced control technique, which has been very successful in particular applications. Model predictive control (MPC) refers to a class of computer control algorithms that control the future behavior of a plant through the use of an explicit process model. At each control interval the MPC algorithm computes an open-loop sequence of manipulated variable adjustments in order to optimize future plant behavior. The Model Predictive Control problem is formulated as solving on-line a finite horizon open

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loop optimal control problem subject to system dynamics and constraints involving states and controls. Fig shows the basic principle of model predictive control. Based on measurements obtained at time *t*, the controller predicts the future dynamic behavior of the system over a prediction horizon *T* and determines (over a control horizon) the input such that a predetermined open-loop performance object function is optimized.

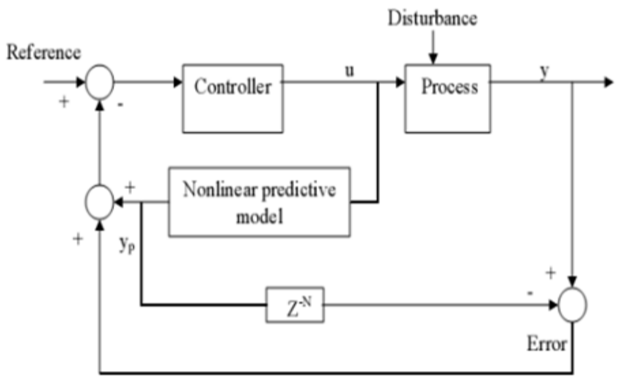

Fig. 1. Block diagram of the MPC system

Model predictive control (MPC) is a very attractive concept for the development and tuning of nonlinear controllers in the presence of input, output or state constraint. The first input in the optimal sequence is injected into the plant, and the entire optimization is repeated at subsequent control intervals. MPC technology was originally developed for power plant and petroleum refinery applications, but can now be found in a wide variety of manufacturing environments including chemicals, food processing, automotive, aerospace, metallurgy and pulp and paper. The application of MPC controllers based on linear dynamic models cover a wide range of applications, and linear MPC theory can be considered quite mature. Nevertheless, many manufacturing processes are inherently nonlinear and there are cases where nonlinear effects are significant and can-not be ignored. These include at least two broad categories of applications: 1. Regulator control problems where the process is highly nonlinear and subject to large frequent disturbances (pH control, etc.). 2. Servo control problems where the operating points change frequently and span a wide range of nonlinear process dynamics (polymer manufacturing, ammonia synthesis, etc.). Model based predictive control, MBPC, strategy has received particular attention in the areas of process control, is based on the use of a model for predicting the future behaviors of the system over a finite future horizon. The control signal to be applied to the plant at the current sampling time is obtained by solving a finite dimension optimization problem over the prediction horizon. “MPC is the family of controllers in which there is a direct use of an explicit and separately identifiable model” The advantages of MPC compared with many other control techniques can be listed as follows:

- It can use step and impulse response data which can easily be obtained,
- It can handle input/output constraints directly,
- It gives satisfactory performance even with time delays and high nonlinearities,
- It can be used in multivariable format,
- It is robust in most cases,
- Implementation of the technique is simple,
- It can optimize over a trajectory,
- It can be used to control various processes, whether simple or complex ones.

Voltage Injection Methods of UPQC

Voltage injection or compensation methods by means of a UPQC depend upon the limiting factors such as; UPQC power ratings, various conditions of load, and different types of voltage sags. Some loads are sensitive towards phase angel jump and some are sensitive towards change in magnitude and others are tolerant to these.

III. PROPOSED SYSTEM

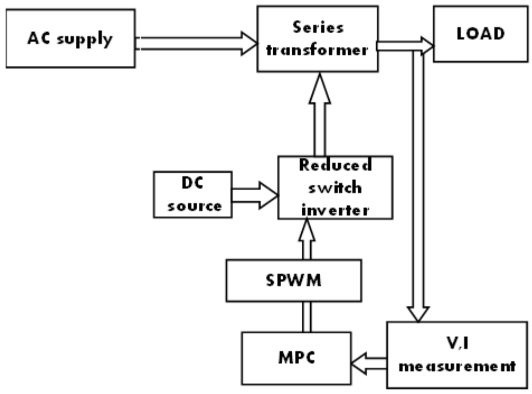

Fig. 2. Proposed block diagram

The proposed topology is an eight-switch conditioner using a hybrid filter in shunt converter (see figure 3) aiming cost reduction when compared with traditional power conditioners.

The eight-switch converter performs the constant measurement of voltage and current from the grid to make control decisions, which are basically the injection signal to compensate the current harmonics and, in case of a voltage sag, increase the range of the carrier dedicated to the series converter to inject the signal for a rated load voltage. In this topology, the compensation of current harmonics is performed by a passive filter in series with an active filter, as shown in figure 3. The passive filter is tuned to the 7^{th} harmonic, having low impedance around this harmonic and high impedance around the switching frequency. The reasons for selecting the 7^{th} harmonic frequency are summarized as follows.

1) The *LC* filter tuned at the 7th harmonic frequency is less bulky and less expensive than that tuned at the 5^{th} harmonic frequency.
2) The 7^{th} harmonic tuned filter presents lower impedances at the 11^{th} and 13^{th} harmonic frequencies than the 5^{th} harmonic tuned filter does.
3) The filtering characteristic for the 5th harmonic frequency can be significantly improved by the feed forward control.

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Converter Analysis

As shown in figure 3, the eight-switch converter is obtained by removing one switch of the third leg of the nine-switch converter and placing the output terminal *C* in the positive pole of the dc link. This is feasible because the capacitors of the *LC* filter block the dc components generated by the connection of one phase to the positive pole of the dc link.

The complementary duty cycle expressions for the series converter are obtained by scaling the complementary duty cycles, given by (2), as follows:

*DR*series =*M*series*DR* (4)

*DR*series =*M*series

*V*Rvdc+12_*. (5)

With the removal of one switch for the shunt converter, the duty cycles of the remaining switches (i.e., *DA* and *DB*) should reflect the synthesis of the line-to-line voltages *v∗AC* and *v*BC*, instead of the phase voltages. A slightly different approach should be carried out for deducing the duty cycles of the eightswitch converter.

Focusing only on the converter leg *AR* of the eight-switch converter (see Fig. 3), it is possible to find that switch *SA* controls the voltage *vAC* as follows:

vAC = (*SA* − 1)*v*dc. (6)

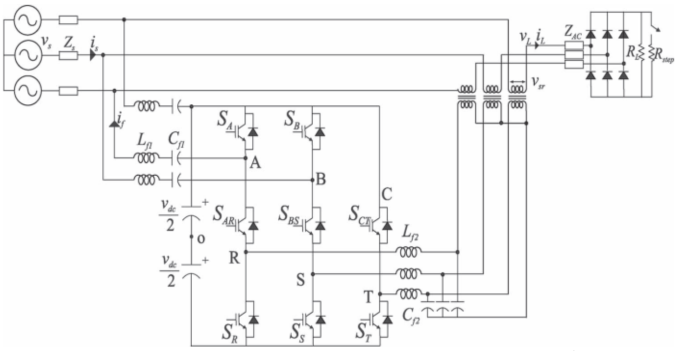

Fig. 3. Proposed eight switch conditioner using the hybrid filter

The duty cycle *DA* of switch *SA* can be determined taking the average value of (6) in one switching period

DA = 1+*v*ACv*dc (7)

where *v*AC* is the line-to-line reference voltage at the output of the eight-switch converter, which is equal to *vAC* (average value) if the switching frequency is sufficiently high.

It is important to mention that the inequality in (3) should be also valid for the eight-switch converter. On the other hand, it is interesting to rearrange such inequality in terms of line-to-line voltages in order to find the boundaries of *v*AC*. Thus,

*V*A*≥ *v*R*⇒ *v*AC* + *v*C*≥ *v*R*. (8)

Observing Fig. 3, it is possible to note that *v*C* = +*v*dc/2.

Therefore,

*V*AC* + *v*dc2≥ *v*R*. (9)

Based on the same approach for the nine-switch converter, the inequality in (9) always holds true if the left side of (9) is always greater than zero, leading to

*V*AC*≥ −*v*dc2 . (10)

In addition, taking into account that *DA* ≤ 1 in (7), it is possible to find that

*v*AC*≤ 0. (11)

Combining both inequalities in (10) and (11) yields

−*v*dc2≤ *v*AC*≤ 0. (12)

For the same reasons exposed for the nine-switch converter it is necessary to shift the sinusoidal waveform in *v* AC*. For the shunt converter, the duty cycle is scaled and shifted as follows:

*DA*shunt = *M*shunt*DA* + (1 −*M*shunt) _ __ _*M*series. (13)

Therefore,

*DA*shunt = 1+*M*shun t

*V*ACv*dc. (14)

The state of the intermediate switch is defined as the *exclusive or* of the top and bottom switches' states, i.e.,

SAR = *SA* * *SR*. (15)

A. Injection Transformer

The injection transformer is presently the prevalent method for connecting the network analyzer to the circuit being tested, and is primarily used for control loop stability measurements. The goal of the transformer is to inject a signal into the control loop being measured, without impacting the performance of the loop. In order to accomplish this to a reasonable degree, the transformer is isolated and therefore is capable of floating on a high voltage, such as a Power Factor Corrector (PFC), which is often close to 400VDC. Measuring voltages that exceed the voltage rating of the Bode-100 inputs require attenuation probes.

B. PWM

Pulse-width modulation (PWM), or pulse-duration modulation (PDM), is a modulation technique used to encode a message into a pulsing signal. Although this modulation technique can be used to encode information for transmission, its main use is to allow the control of the power supplied to electrical devices, especially to inertial loads such as motors. In addition, PWM is one of the two principal algorithms used in photovoltaic solar battery chargers, the other being MPPT. The average value of voltage (and current) fed to the load is controlled by turning the switch between supply and load on and off at a fast rate. The longer the switch is on compared to the off periods, the higher the total power supplied to the load. The PWM switching frequency has to be much higher than what would affect the load (the device that uses the power), which is to say that the resultant waveform perceived by the load must be as smooth as possible. Typically switching has to be done several times a minute in an electric stove, 120 Hz in a lamp dimmer, from few kilohertz (kHz) to tens of kHz for a motor drive and well into the tens or hundreds of kHz in audio amplifiers and computer power supplies.

C. Microcontroller

The AVR is a modified Harvard architecture 8-bit RISC single-chip microcontroller, which was developed by Atmel in 1996. The AVR was one of the first microcontroller families to use on-chip flash memory for program storage, as opposed to one-time programmable ROM, EPROM, or EEPROM used by other microcontrollers at the time.

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IV. Circuit Diagram and Description

A. Potential Transformers

Voltage transformers (VT) or potential transformers (PT) are another type of instrument transformer, used for metering and protection in high-voltage circuits. They are designed to present negligible load to the supply being measured and to have a precise voltage ratio to accurately step down high voltages so that metering and protective relay equipment can be operated at a lower potential. Typically the secondary of a voltage transformer is rated for 69 V or 120 V at rated primary voltage, to match the input ratings of protective relays.

The transformer winding high-voltage connection points are typically labeled as H_1, H_2 (sometimes H_0 if it is internally grounded) and X_1, X2 and sometimes an X_3 tap may be present. Sometimes a second isolated winding (Y_1, Y_2, Y_3) may also be available on the same voltage transformer. The high side (primary) may be connected phase to ground or phase to phase. The low side (secondary) is usually phase to ground.

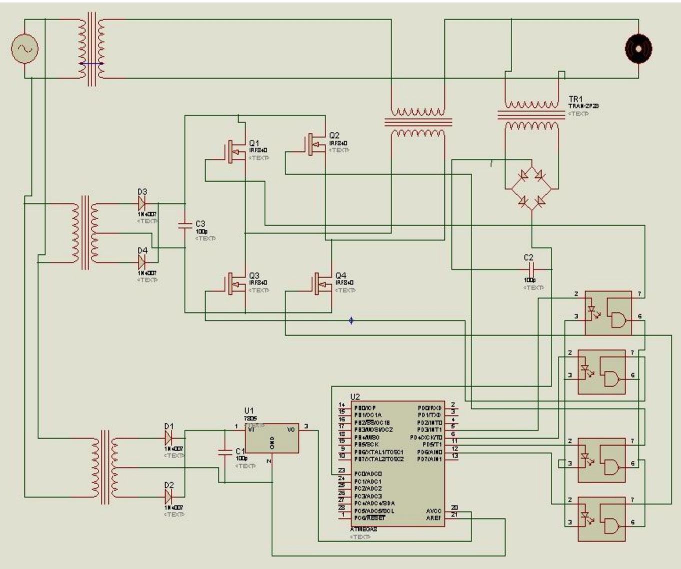

Fig. 4. Hardware implementation

B. Step Up Transformer

Step-up transformer 110v 220v design is one whose secondary voltage is greater than its primary voltage. This kind of transformer "steps up" the voltage applied to it. For instance, a step up transformer is needed to use a 220v product in a country with a 110v supply.

Step-up transformer 110v 220v depends entirely on the products you will be using it with. Give transformer supplier a detailed list of all the products will be using with it - and also their maximum outputs. From this information he/she will be able to advise the correct step up transformer rating needed.

C. Inverter

A power inverter, or inverter, is an electronic device or circuitry that changes direct current (DC) to alternating current (AC). The input voltage, output voltage and frequency, and overall power handling depend on the design of the specific device or circuitry. The inverter does not produce any power; the power is provided by the DC source. Here IGBT circuit is used as inverter. A power inverter can be entirely electronic or may be a combination of mechanical effects (such as a rotary apparatus) and electronic circuitry

V. Simulations and Results

Simulation results are presented to demonstrate the practical operation of the eight-switch conditioner. The distribution power system is represented by its Thévenin equivalent using typical values, and the power conditioner feeds a nonlinear load, as shown in Fig. 3. The parameters used in the simulation results are summarized. The simulation software used in this paper is MATLAB/Simulink.

The first result shows the grid and load currents, thus demonstrating the effectiveness of the converter in the compensation of current harmonics. The total harmonic distortion (THD) of load current is 24.86%, whereas the grid current shows harmonic distortion of 3.68%, being within the limit of 5% recommended by IEEE 519-1992. The compensation process during a load change is shown in figure In this case, resistors are connected in parallel with the diode rectifier. The dc-link voltage is also shown to confirm good controller performance. The results were obtained without voltage sag in the grid. It is noteworthy that the compensation of harmonic currents is not priority when you have disturbances in the voltages of the grid.

TABLE I. Sysem parameters

S. No.	System Quantities	Standards
1.	Three phase source	13KV, 50Hz.
2.	Step-up transformer	Y-Δ , 13/115KV
3.	Transmission line parameter	R=0.001 ohms,L=0.005 H
4.	Step-down transformer	Δ-Y, 115/11KV
5.	Load 1 &2	10KW, 400VAR
6.	Inverter	IGBT based,3 arms , 6 Pulse, Carrier Frequency =1080 Hz, Sample Time= 5 µs
7.	DC battery	6.5 KV
8.	C_2	750 µF
9.	Linear/Isolation transformer	1:1 turns ratio, 11/11KV

The first simulation was done with no UPQC and results are obtained as shown in figure.

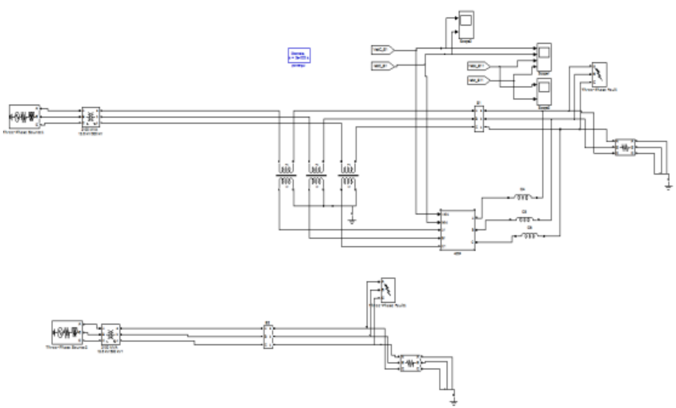

Fig. 5. Simulation diagram

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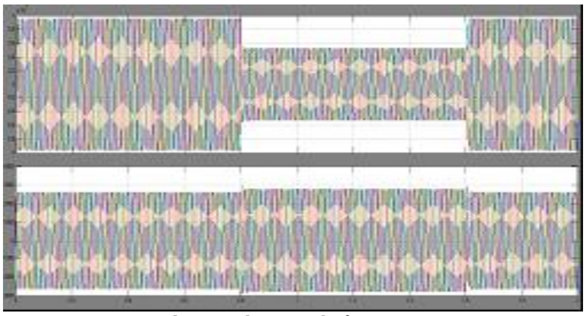

Fig. 6. Voltage and current before compensation

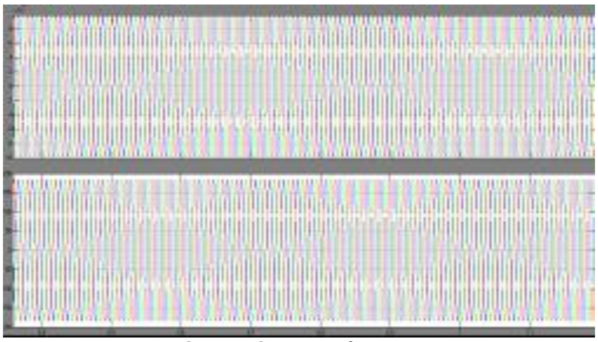

Fig. 7. Voltage and current after compensation

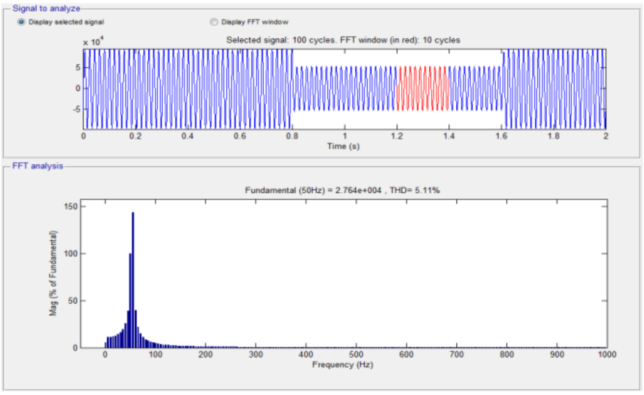

Fig. 8. Before harmonics compensation

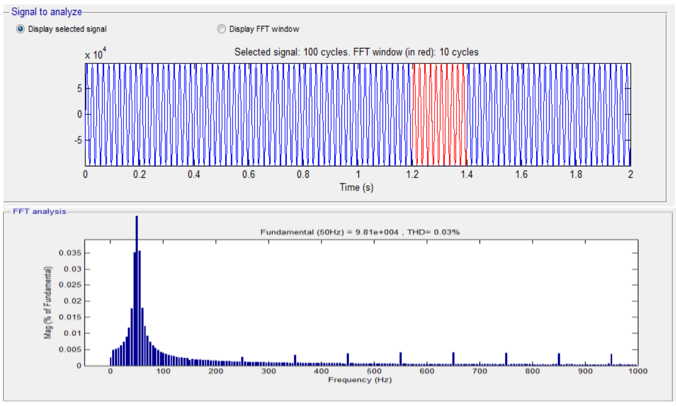

Fig. 9. After harmonics compensation

VI. Conclusion

In order to show the performance of UPQC in mitigation of voltage sags, is simple distribution network is simulated using MATLAB and to verify the results of hardware implementation. A UPQC is connected to a system through a series transformer with a capability to insert a maximum voltage of 50% of phase to ground system voltage. In-phase compensation method is used. UPQC handles both balanced and unbalanced situations without any difficulties and injects the appropriate voltage component to correct rapidly any deviation in the supply voltage to keep the load voltage constant at the nominal value. The main advantages of the proposed UPQC are simple control, fast response and low cost. The proposed PWM control scheme using Model predictive controller is efficient in providing the voltage sag compensation. As opposed to fundamental frequency switching schemes already available in the MATLAB/SIMULINK, this PWM control scheme only requires voltage measurements. This characteristic makes it ideally suitable for low-voltage custom power applications. UPQC works independently of the type of fault as tested for the system as based on the analysis of test system UPQC mitigates voltage sags due to three phase, single L-G and double line faults. The main shortcoming of the UPQC, being a series device, is its inability to mitigate complete interruptions.

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