Performance of PI and Artificial Neural Network Controllers On Unified Power-Quality Conditioner

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Abstract: This paper discusses about a comparative study of performance of Unified Power-Quality Conditioner (UPQC) with PI and Artificial Neural Network (ANN) controllers. UPQC is a electronic device consisting of an active power filter (APF) , used for compensation of various Power Quality (PQ) problems such as harmonic filtering, damping, isolation and termination, load balancing, reactive-power control for power-factor correction and voltage regulation, voltage-flicker reduction or their combinations. The output control signals from the UPQC necessary are derived with the use of various control strategies. Here a simple feed forward type ANN is used a control strategy for providing the necessary control signals for the accurate and fast operation of UPQC. The algorithm for training the neural network is developed from the data with conventional PI controller. The simulation is carried out in MATLAB/SIMULINK and the results of ANN controller are compared with that of a conventional PI controller.

1. Introduction

The use of nonlinear and impact loads bring about harmonics and reactive power loading variance in power system, which has a strong impact on the other loads in the same system. Employment of UPQC (unified power quality conditioner) could decrease impact on transmission and distribution harmonics and neutral-line current caused by unbalance and nonlinear load, enhance custom power quality meanwhile supply balance and sinusoidal voltage to load and enhance power distribution reliability. Usually there are two control scheme of UPQC, one is most used, known as indirect control strategy, in which series compensator work by way of voltage source, compensating mainly voltage distortion and fundamental wave deviation, supplying rated balance sinusoidal voltage for load, and shunt compensator as current source, compensating the harmonics, reactive current in load. The other is direct control strategy, in which series compensator work as sinusoidal current source, shunt compensator as sinusoidal voltage source.

The power factor of power line can be unity because of series compensation current having the same phase with system voltage and the load can get balance, rated sinusoidal voltage. Employing this strategy, series compensator isolate the voltage disturbance between power line and load, as well as shunt compensator prevent the reactive power, harmonic and neutral current on the load side into power line .Additionally, another benefit from the direct control strategy is that it is not necessary to change the work mode when power line dumping or restoring, for shunt compensator all along is controlled as sinusoidal voltage source.

1.2 Power Quality

Synchronization of the voltage frequency and phase allows electrical systems to function in their intended manner without significant loss of performance or life. Power quality determines the fitness of electrical power to consumer devices. The term is used to describe electric power that drives an electrical load and the load's ability to function properly. Without the proper power, an electrical device (or load) may malfunction, fail prematurely or not operate at all. There are many ways in which electric power can be of poor quality and many more causes of such poor quality power.

The electricity then moves through the wiring system of the end user until it reaches the load. The complexity of the system to move electric energy from the point of production to the point of consumption combined with variations in weather, generation, demand and other factors provide many opportunities for the quality of supply to be compromised.

While "power quality" is a convenient term for many, it is the quality of the voltage rather than power or electric current that is actually described by the term. Power is simply the flow of energy and the current demanded by a load is largely uncontrollable.

The quality of electrical power may be described as a set of values of parameters, such as:

- Continuity of service
- Variation in voltage magnitude
- Transient voltages and currents
- Harmonic content in the waveforms for AC power

Custom Power devices are used in distribution level. Unlike FACTS, their purpose is more to improve the quality of the service and protect sensitive loads against disturbance of the supply. A wide range of very flexible controllers, which capitalize on newly available power electronics components, are emerging for custom power applications. Among these, the Distribution Static Compensator (DSTATCOM) and the Dynamic Voltage Restorer (DVR), both of them based on the Voltage Source Converter (VSC) principle, and the Solid State Switches (SSS). Unified power quality conditioner is widely studied by many researchers as an eventual method to improve power quality of electrical distribution system. The function of unified power quality conditioner is to eliminate the disturbances that affect the performance of the critical load in power system. In other words, the UPQC has the capability of improving power quality at the point of installation on power distribution systems. The UPQC therefore, is expected to be one of the most powerful solutions to large capacity loads sensitive to supply voltage flicker/imbalance. The UPQC, which has two inverters that share one dc link, can compensate the voltage sag and swell, the harmonic current and voltage, and control the power flow and voltage stability. Besides, the UPQC can also compensate the voltage interruption if it has some energy storage or battery in the dc link.

1.3 Controllers

The controllers which are used for the control of outputs of the converters are basically categorized into two types.
They are:

- Conventional controllers
- Advanced controllers

Conventional controllers which are basically static controllers are the forms of mathematical functions consisting of various parameters whose outputs depend on these parameters. These controllers include P (proportional) controller, PI (proportional plus integral) controller and PID (proportional plus integral plus derivative) controllers.

Advanced controllers are sophisticated controllers and are capable of adapting to the situations. These are popular because of their advantages like

- Can handle large nonlinear and imprecise data.
- Can generate more precise and accurate outputs by performing more number of iterations.

These type of controllers include Artificial Neural Network (ANN) controllers, Fuzzy logic controllers and RST controllers.

2. Control of UPQC

From the basic block diagram of the UPQC below, the shunt and series bidirectional converters which act as inverters under operating mode should act in accordance with the condition's severity. Hence the PWM signals which control the inverter outputs have to be varied and for this the knowledge of the actual and desired parameters is necessary.

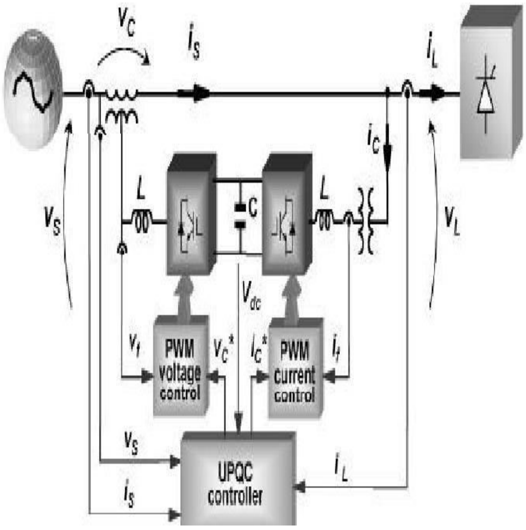

Fig 5.1 Basic control scheme for the UPQC

For such knowledge of the varied PWM signals a external controller is to be used which generate variety of signals based on the severity of difference of the actual and desired line parameters.

Hence the external controllers necessary can be broadly classified as

- Conventional controllers
- Advanced controllers

2.1 Conventional controller

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2.2 PI Controller:

Like the P-Only controller, the Proportional-Integral (PI) algorithm computes and transmits a controller output (CO) signal every sample time, T, to the final control element (e.g., valve, variable speed pump). The computed CO from the PI algorithm is influenced by the controller tuning parameters and the controller error, e(t). PI controllers have two tuning parameters to adjust. While this makes them more challenging to tune than a P-Only controller, they are not as complex as the three parameter PID controller.

Integral action enables PI controllers to eliminate offset, a major weakness of a P-only controller. Thus, PI controllers provide a balance of complexity and capability that makes them by far the most widely used algorithm in process control applications.

2.3 The PI Algorithm

While different vendors cast what is essentially the same algorithm in different forms, here we explore what is variously described as the dependent, ideal, continuous, position form:

$$CO = CO_{bias} + Kc \cdot e(t) + \frac{Kc}{Ti}\int e(t)dt$$

CO = controller output signal (the wire out)
CO_{bias} = controller bias or null value; set by bumpless transfer as explained below
e(t) = current controller error, defined as SP – PV
SP = set point
PV = measured process variable (the wire in)
Kc = controller gain, a tuning parameter
*T*i = reset time, a tuning parameter

The first two terms to the right of the equal sign are identical to the P-Only controller referenced at the top of this article.

The integral mode of the controller is the last term of the equation. Its function is to integrate or continually sum the controller error, e(t), over time.

2.4 Artificial Neural-networks

The term 'neural network' is in fact a biological term, and what we refer to as neural networks should really be called Artificial Neural Networks (ANNs).

Design of PI controller

For the design of the PI controller taking the help of the block diagram of the Unified Power Quality Conditioner (UPQC).

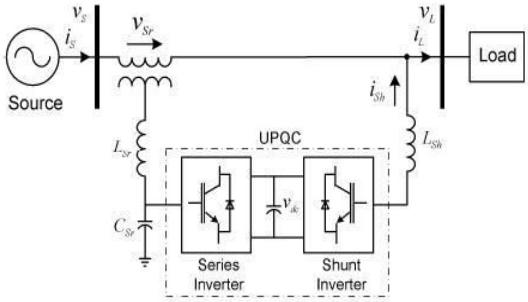

Fig. 5.11 Block diagram representation for the design of PI controller

The design of PI controller for current source inverter is done by the following assumptions

1) The voltage at PCC is sinusoidal and balanced.
2) Since the harmonic component does not affect the average power balance expressions, only the fundamental component of currents is considered.
3) Losses of the system are lumped and represented by an equivalent resistance connected in series with the filter inductor.
4) Ripples in the dc-link current are neglected.

The average rate at which energy being absorbed by the inductor is
$P_{ind} = ½ (d/dt (L_{dc} I_{dc}^2)) = L_{dc}I_{dc} d/dt(I_{dc})$
The power input to the PWM converter
$P_{conv} = 3V_{sh}I_{inj}$
The average rate of change of energy associated with the capacitor filter
$P_{cap} = ½ (d/dt (C_{sh}V_{sh}^2))$
Power loss in the resistor Rsh
$P_{loss} = 3I_{inj}^2 R_{sh}$

Equating them
$P_{ind} = P_{conv} - P_{loss} - P_{cap}$
Substituting the values
$L_{dc}I_{dc} d/dt(I_{dc}) = 3(V_{sh}I_{inj} - I_{inj}^2R_{sh} - C_{sh}V_{sh} d/dt(V_{sh}))$

In order to linearize the power equation, a small perturbation ΔI_{inj} is applied in the input current I_{inj} of converter about a steady-state operating point I_{injo}, the average dc-link current will also get perturbed by a small amount ΔIdc around its steady-state operating point I_{dco}

$I_{inj} = I_{injo} + \Delta I_{inj}$ and $I_{dc} = I_{dco} + \Delta I_{dc}$

In the above equation neglecting higher order terms
$L_{dc}I_{dco}(d/dt(\Delta Idc)) = 3(V_{sh}I_{injo} + V_{sh}\Delta I_{inj} - I_{injo}^2R_{sh} - 2I_{inj}\Delta I_{injo}R_{sh} - C_{sh}V_{sh} d/dt(V_{sh}))$

Subtracting the above two equations
$L_{dc}I_{dc} d/dt(\Delta I_{dc}) = 3(V_{sh}\Delta I_{inj} - 2I_{inj}\Delta I_{injo}R_{sh} - C_{sh}V_{sh} d/dt(V_{sh}))$

The transfer function of the PWM converter for a particular operating point
$K_c = (\Delta I_{dc}/\Delta I_{inj}) = 3((V_{sh} - C_{sh}V_{sh}\mathbf{s} - 2 I_{injo}R_{sh})/(L_{dc}I_{dco}\mathbf{s}))$
The characteristic equation of Pi controller is
$1 + (K_p + K_i/\mathbf{s}) 3 ((V_{sh} - C_{sh}V_{sh}\mathbf{s} - 2I_{injo}R_{sh}) / (L_{dc}I_{dco}\mathbf{s})) = 0$

Some of the parameters are taken as
V_{sh}=230V, I_{injo}=5 amp, R_{sh}=0.4Ω, C_{sh}=24μF,
L_{dc}=160mH, I_{dco}=5 amp
Hence the characteristic equation on substitution of the values is
$0.8\mathbf{s}^2 + K_p(678 - 0.0165\mathbf{s}^2) + K_i(678 - 0.0165\mathbf{s})$

Using Routh Hurwitz criteria the values of Kp =0.5 and Ki =10 are chosen for the PI controller that is used in UPQC.

2.6. Design of ANN controller

In the ANN controller, very popular Levenberg–Marquardt back propagation (LMBP) algorithm is used for training the neural network This is supervised fast training algorithm, and requires less memory than other algorithms.

3 Problem and solution of the LMBP algorithm

3.1 Problem

The primary application of the Levenberg–Marquardt algorithm is in the least squares curve fitting problem: given a set of m empirical datum pairs of independent and dependent variables, (x_i, y_i), optimize the parameters β of the model curve $f(x,\boldsymbol{\beta})$ so that the sum of the squares of the deviations becomes minimum.

$$S(\boldsymbol{\beta}) = \sum_{i=1}^{m} [y_i - f(x_i,\ \boldsymbol{\beta})]^2$$

3.2 Solution

Like other numeric minimization algorithms, the Levenberg–Marquardt algorithm is an iterative procedure. To start a minimization, the user has to provide an initial guess for the parameter vector, $\boldsymbol{\beta}$. In cases with only one minimum, an uninformed standard guess like $\boldsymbol{\beta}^T$=(1,1,...,1) will work fine; in cases with multiple minima, the algorithm converges only if the initial guess is already somewhat close to the final solution.

In each iteration step, the parameter vector, $\boldsymbol{\beta}$, is replaced by a new estimate, $\boldsymbol{\beta} + \boldsymbol{\delta}$. To determine $\boldsymbol{\delta}$, the functions $f(x_i, \boldsymbol{\beta} + \boldsymbol{\delta})$ are approximated by their linearizations

$$f(x_i, \boldsymbol{\beta} + \boldsymbol{\delta}) \approx f(x_i, \boldsymbol{\beta}) + J_i\boldsymbol{\delta}$$

where

$$J_i = \frac{\partial f(x_i, \boldsymbol{\beta})}{\partial \boldsymbol{\beta}}$$

is the gradient (row-vector in this case) of f with respect to $\boldsymbol{\beta}$.

At the minimum of the sum of squares, $S(\beta)$, the gradient of S with respect to $\boldsymbol{\delta}$ will be zero. The above first-order approximation of $f(x_i, \boldsymbol{\beta} + \boldsymbol{\delta})$ gives

$$S(\beta + \delta) \approx \sum_{i=1}^{m} \left(y_i - f(x_i, \beta) - J_i\delta\right)^2 .$$

Or in vector notation,

$$S(\boldsymbol{\beta}+\boldsymbol{\delta}) \approx \|\mathbf{y}-\mathbf{f}(\boldsymbol{\beta})-\mathbf{J}\boldsymbol{\delta}\|^2.$$

Taking the derivative with respect to **δ** and setting the result to zero gives:

$$(\mathbf{J}^{\mathbf{T}}\mathbf{J})\boldsymbol{\delta} = \mathbf{J}^{\mathbf{T}}[\mathbf{y}-\mathbf{f}(\boldsymbol{\beta})]$$

where $\mathbf{J}$ is the Jacobian matrix whose i^{th} row equals J_i, and where $\mathbf{f}$ and $\mathbf{y}$ are vectors with i^{th} component $f(x_i, \boldsymbol{\beta})$ and y_i, respectively. This is a set of linear equations which can be solved for $\boldsymbol{\delta}$.

Levenberg's contribution is to replace this equation by a "damped version",

$$(\mathbf{J}^{\mathbf{T}}\mathbf{J}+\lambda\mathbf{I})\boldsymbol{\delta} = \mathbf{J}^{\mathbf{T}}[\mathbf{y}-\mathbf{f}(\boldsymbol{\beta})]$$

where **I** is the identity matrix, giving as the increment, $\boldsymbol{\delta}$, to the estimated parameter vector, $\boldsymbol{\beta}$.

The (non-negative) damping factor, λ, is adjusted at each iteration. If reduction of S is rapid, a smaller value can be used, bringing the algorithm closer to the Gauss–Newton algorithm, whereas if an iteration gives insufficient reduction in the residual, λ can be increased, giving a step closer to the gradient descent direction. Note that the gradient of S with respect to $\boldsymbol{\beta}$ equals $-2(\mathbf{J}^T[\mathbf{y}-\mathbf{f}(\boldsymbol{\beta})])^T$. Therefore, for large values of λ, the step will be taken approximately in the direction of the gradient. If either the length of the calculated step, $\boldsymbol{\delta}$, or the reduction of sum of squares from the latest parameter vector, $\boldsymbol{\beta}+\boldsymbol{\delta}$, fall below predefined limits, iteration stops and the last parameter vector, $\boldsymbol{\beta}$, is considered to be the solution.

Levenberg's algorithm has the disadvantage that if the value of damping factor, λ, is large, inverting $\mathbf{J}^T\mathbf{J}+\lambda\mathbf{I}$ is not used at all. Marquardt provided the insight that we can scale each component of the gradient according to the curvature so that there is larger movement along the directions where the gradient is smaller. This avoids slow convergence in the direction of small gradient.

Therefore, Marquardt replaced the identity matrix, **I**, with the diagonal matrix consisting of the diagonal elements of $\mathbf{J}^T\mathbf{J}$, resulting in the Levenberg–Marquardt algorithm:

$$(\mathbf{J}^{\mathbf{T}}\mathbf{J}+\lambda\,\mathrm{diag}(\mathbf{J}^{\mathbf{T}}\mathbf{J}))\boldsymbol{\delta} = \mathbf{J}^{\mathbf{T}}[\mathbf{y}-\mathbf{f}(\boldsymbol{\beta})].$$

4. Simulation of Uncompensated Three Phase System

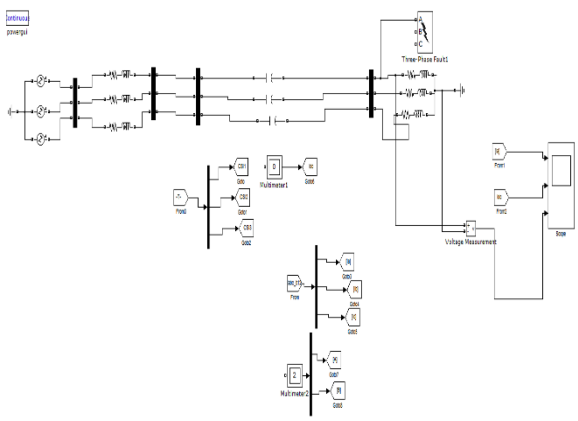

Fig 4.1 Simulink diagram of three phase system with single line to ground fault

The above diagram represents the simulink model of a three phase three wire power system network with a Single Line to Ground (SLG) fault. The source and load side disturbances are studied due to the fault.

4.1Simulation Waveforms of the Uncompensated System

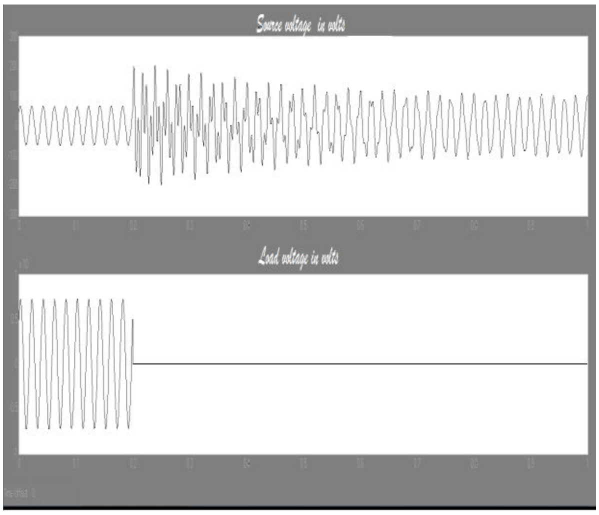

Fig 4.2 Simulation waveforms of the Uncompensated Three Phase System

The above diagram gives the Load and source side waveforms of the Uncompensated three phase system.

The first waveform represents the Source voltage in volts, and the last waveform represents the load voltage in volts. The single line to ground fault causes a zero voltage across the load as represented in the waveform.

4.2 UPQC connected three phase system

4.3 With PI controller

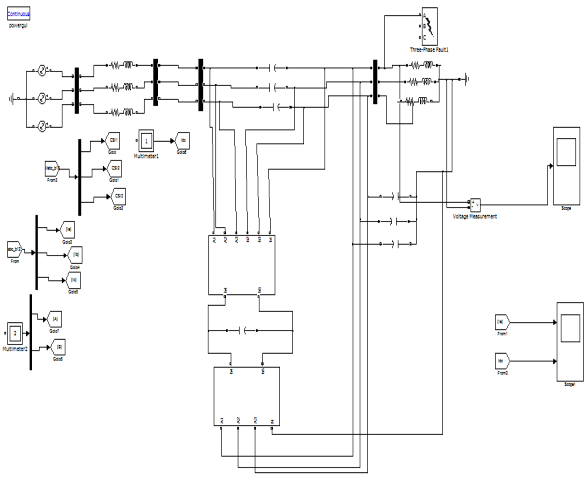

Fig.4.3 Simulink diagram of PI controlled UPQC connected Three phase system

The above figure is the Simulink model of the UPQC connected System with the action of the PI controller for the external control of the UPQC.

4.3 Simulation results of the PI controlled UPQC connected system

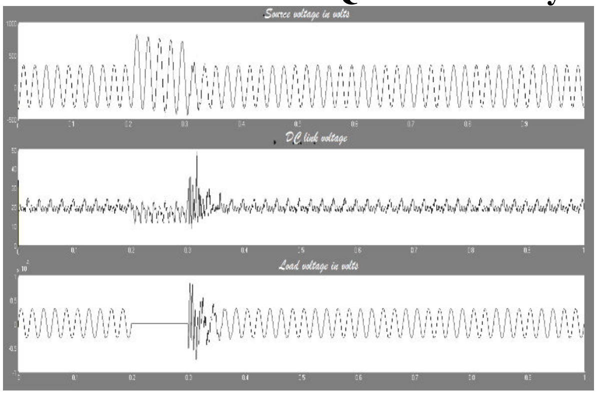

Fig. 4.4 Simulation waveforms of the PI controlled UPQC connected Three Phase system

The above waveforms prove that UPQC is able to compensate the various faults on the system. The source side disturbances as well as the load side disturbances are compensated and the load voltage appears within a short duration. Hence the fault is cleared.

4.5 With ANN controller

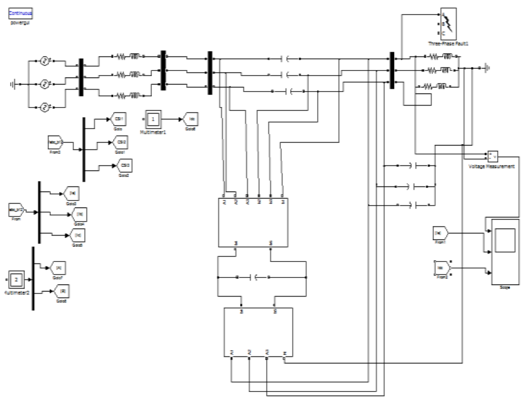

Fig 4.5 Simulink diagram of the ANN controlled UPQC connected System

The above network represents the ANN controlled UPQC connected to a three phase system with a SLG fault. Here the ANN controller is used for the external control of the UPQC.

4.6 Simulation results of the ANN controlled UPQC connected system

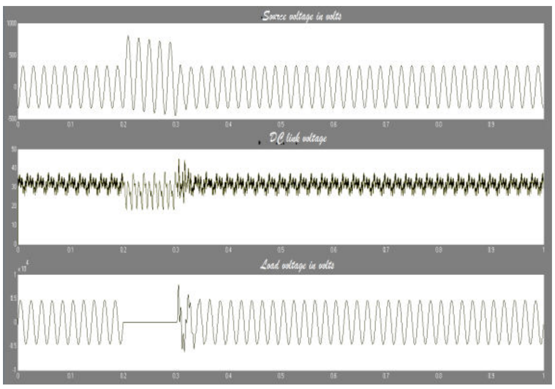

Fig 4.6 Simulation waveforms of ANN controlled UPQC connected system

The above figures show the source, dc link and the load voltage waveforms of ANN controlled UPQC connected to a three phase system with a SLG fault. The ANN controller is fast and hence can clear the fault within less time than a PI controller.

5. CONCLUSION

Unified Power Quality Conditioner is a power quality compensator that provides compensation for both the voltage and current related problems simultaneously. The external controllers used for the derivation of the reference signals for the fast and accurate operation of UPQC when used individually may show unsatisfactory performance in one or the other conditions.

Hence we can use the combination of one or more controllers that is cascading controllers, here in case of our work ANN and PI controllers can be cascaded together to provide still better performance.

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