Simulation of series active filter for unbalanced loads

P.KALAIVANI M.E (P.S.E)

Power system engineering

Anna University

Guindy, Chennai-600025

Tamil Nadu

INDIA

greatkalai_sasi@yahoo.co.in and sasikumarkalai@gmail.com

Abstract: - The use of power electronics circuits in a wide range of applications has resulted in distorted current waveforms in the power system. This result in non-sinusoidal voltage drops across the transformers and transmission line impedances, resulting in a non-sinusoidal voltage supply at the point of common coupling. Asymmetrical distribution of large single phase loads further complicates the issue by causing unbalance in the line currents of the three phase system. Unbalance in load current leads to excessive neutral currents, power factor, increased losses and reduced in overall efficiency. The use of series active filter in the load side to mitigate the unbalance in the system. Hear we use proposed optimization technique for balancing the currents and obtaining the best compromise between the power factor and current distortion under non-sinusoidal voltage conditions. It does not use p-q theory.

Key-Words: - Harmonics, Non-sinusoidal voltage, Optimization, Power factor, Series active Filter, Unbalance

1. Introduction

A series active filter (SAF), shown in Fig.1, can be used to compensate for both harmonic distortion and imbalance in the supply voltage. The voltages, either on the supply side or the load side, can be compensated as desired. However, this paper deals with applications where the loads are sensitive to voltage waveform quality. Hence, the compensation is considered only on the load side. The compensation voltages, required to eliminate voltage harmonics and make the system balanced, are injected across the compensating transformers’ secondary windings which are in series with the line.

It can be observed that if an attempt is made to reduce the voltage THD, the power factor may decrease, while any attempt at achieving a higher power factor may result in higher voltage THD. This tradeoff between the power factor and voltage distortion (THD) must be optimized to achieve the best compromise.

Thus, there is a tradeoff between the power factor and voltage THD and a suitable optimization [10], [11] of the two is necessary. The proposed scheme also has the following desirable features.

i) An optimized power factor.
ii) An optimized voltage total harmonic distortion (THD) which is within the limit stipulated by power quality norms.
iii) A balanced source current
2. Proposed compensation technique

Consider a power system with a nonlinear load being supplied with a non-sinusoidal supply voltage. Let the supply voltage $v_{sa}$ contain $n$ harmonic components that produce a load current of identical frequencies and another $n$ components that do not result in the corresponding load current components. The corresponding expression for voltage may be written as

$$v_{sa} = \sqrt{2} \sum_{1}^{n} V_{san} \sin\left(n \omega t + \alpha_n\right)$$  \hspace{1cm} (1)

Where $\alpha_n$ is the arbitrary angle of the supply voltage and $V_{san}$ is the root-mean-square value of the $n$th order harmonic component of voltage.

Let the load current contain $n$ components of current, having no corresponding frequency components in the supply voltage, due to their non linearity. Also, for simplicity, assume that there is no phase angle between the voltage and the current harmonic. The corresponding expression for current may be written as

$$i_{sa} = \sqrt{2} \sum_{1}^{n} I_{san} \sin\left(n \omega t + \alpha_n - \psi_n\right)$$  \hspace{1cm} (2)

Where $I_{san}$ is the rms value of the $n$th order harmonic component of source current and $\psi_n$ is the phase angle between voltage and current of the corresponding harmonic components. For achieving an optimum power factor, an expression for the desired load voltage $V_{la}^*$ is obtained by using (2), by setting the order of harmonics present in the supply voltage the same as that of current. This means that the harmonic components represented by $n$ in the supply voltage should be replaced by the order of harmonics present in the current. The expression for the desired load voltage after compensation is

$$V_{la}^* = \sqrt{2} \sum_{1}^{n} V_{lan} \sin\left(n \omega t + \alpha_n\right)$$  \hspace{1cm} (3)

where $V_{lan} = I_{san} K_{an}$ and $K_{an}$ are the control variable which is a real quantity and is defined as the ratio of the $n$th order load voltage and current harmonic components and identified as an impedance of the $n$th order after compensation. By controlling $K_{an}$, both the power factor and voltage THD can be controlled and optimized. The most appropriate value of $K_{an}$ is computed by using an optimization technique.

The reference compensating voltage is given by $v_c^* = v_{sa} - v_{la}^*$ where $v_{sa}$ is the supply or load voltage before compensation, $v_{la}^*$ is the desired voltage across the load, and $v_c^*$ is the reference compensation voltage which must be injected across the compensation transformer windings to compensate the supply voltage.

3. Optimization technique

The Lagrangian multiplier optimization technique is used to optimize the nonlinear equation for volt-ampere (apparent power) subject to equality and inequality constraints. Real power demanded by the load is taken as equality constraint and voltage THD limit as the inequality constraint. An augmented Lagrange function can be written as

$$L = f + \lambda g + \mu u$$ \hspace{1cm} (4)

Where $f$ is the objective function, $g$ is the equality constraint, $u$ is the inequality constraint, and $\lambda$ and $\mu$ are to be determined.

The necessary condition for constrained local minima of $L$ is that the
derivative of (4) with respect to its variables should be zero. Since the inequality constraint is also present, Kuhn–Tucker conditions must be satisfied. For minimum apparent power, all of the eigenvalues of the Hessian matrix, evaluated at an optimum value of $K_{an}$, should be positive.

**3.1. Objective Function**

Let $I_{an}$ be the rms value of the current represented by (2) and $V_{la}$ be the rms value of the voltage represented by (3). For given active power, the power factor can be improved by minimizing $S_{an}^2$, the total apparent input power. Thus, the objective function $f$ is constructed as

$$f = S_{an}^2 = \sum_{n=1}^{n} V_{an}^2 \sum_{n=1}^{n} I_{san}^2$$  \hspace{1cm} (5)

Where $V_{an} = I_{san} K_{an}$

Similarly for other phases $S_{ba}^2$ and $S_{cn}^2$, $K_{an}$, $K_{ba}$ and $K_{cn}$ are control variable

**3.2. Equality Constraints**

The magnitude of $V_{la}$ is calculated in such a way that it supplies the mean value of the instantaneous real power demanded by the load. Therefore, the equality constraints can be written as

$$g_a = \frac{P_{dc}}{3} - \sum_{n=1}^{n} I_{san}^2 K_{an} = 0$$  \hspace{1cm} (6)

Similarly for other phases.

$$P_{dc} = \sum_{n=1}^{n} V_{an} I_{san} \cos(\psi_{an}) + \sum_{n=1}^{n} V_{bn} I_{sbn} \cos(\psi_{bn})$$

$$+ \sum_{n=1}^{n} V_{cn} I_{snc} \cos(\psi_{cn})$$  \hspace{1cm} (7)

**3.3. Inequality Constraints**

Let the voltage THD be limited to $V_{THD}$. The inequality constraint ($u_a$) is calculated as

$$u_a = \sum_{n=1}^{n} V_{an}^2 \sqrt{V_{a1}^2} \leq V_{THD}^2$$

$$u_a = \sum_{n=1}^{n} K_{an}^2 I_{san}^2 - V_{THD}^2 K_{a1}^2 I_{sa1}^2 \leq 0$$  \hspace{1cm} (8)

**3.4. Lagrange Function**

The objective is to minimize $S_{an}^2$, given by (5), subject to the equality constraint (6) and the inequality constraint (8). Thus, the augmented function ($L$) is given by

$$L_a = \sum_{n=1}^{n} I_{san}^2 \sum_{n=1}^{n} K_{an}^2 I_{san}^2 + \lambda \left( \frac{P_{dc}}{3} - \sum_{n=1}^{n} I_{san}^2 K_{an} \right)$$

$$+ \mu \left( \sum_{n=2}^{n} K_{an}^2 I_{san}^2 - V_{THD}^2 K_{a1}^2 I_{sa1}^2 \right)$$  \hspace{1cm} (9)

Where $\lambda$ and $\mu$ are the variables corresponding to the equality and inequality constraints. The necessary conditions for constrained local minima of $L$ are

$$\frac{\partial L_a}{\partial K_{a1}} = b_1 \left[ 2 K_{a1} (a - V_{THD}^2 \mu_a) - \lambda_a \right] = 0$$  \hspace{1cm} (10)

$$\frac{\partial L_a}{\partial K_{an}} = b_n \left[ 2 K_{an} (a + \mu_a) - \lambda_a \right] = 0$$  \hspace{1cm} (11)

$$\frac{\partial L_a}{\partial \lambda_a} = g_a = 0$$

$$\frac{\partial L_a}{\partial \mu_a} = u_a \leq 0$$  \hspace{1cm} (13)

Where

$$a = \sum_{n=1}^{n} I_{san}^2 \hspace{1cm} \text{and} \hspace{1cm} b = I_{san}^2$$

Solve the above four equation we find the control variable equations are as

$$K_{a1} = \frac{\lambda_a (V_{THD} I_{san} + I_{sa1})}{2 I_{sa1} \sum_{n=1}^{n} I_{san}^2 \left(1 + V_{THD}^2 \right)}$$  \hspace{1cm} (14)

$$K_{an} = \frac{\lambda_a V_{THD} (V_{THD} I_{san} + I_{sa1})}{2 I_{sa1} \sum_{n=1}^{n} I_{san}^2 \left(1 + V_{THD}^2 \right)}$$  \hspace{1cm} (15)

$$\lambda_a = \frac{2 P_{dc} \sum_{n=1}^{n} I_{san}^2 \left(1 + V_{THD}^2 \right)}{3 \left(V_{THD} I_{san} + I_{sa1} \right)}$$  \hspace{1cm} (16)

The flow chart of proposed algorithm is shown in below
4. Simulation results

The proposed algorithm is verified using MATLAB simulations on a balanced, three phase, 50-Hz, 415-V sinusoidal voltage power supply. The simulation waveforms and readings are shown below.

4.1. Simulation parameter

Source

Line voltage $V_s=415$ V
Fundamental frequency, $f=50$ Hz
Source inductance, $L_s=40\,\text{mH}$
Source $X/R$ ratio, $\approx 8$

Load

Unbalanced RL load

$R_{\text{la}} = 50\,\Omega$, $L_{\text{la}} = 200\,\text{mH}$
$R_{\text{lb}} = 75\,\Omega$, $L_{\text{lb}} = 225\,\text{mH}$
$R_{\text{lc}} = 25\,\Omega$, $L_{\text{lc}} = 175\,\text{mH}$

Nonlinear load

Three phase diode rectifier

$R_d = 125\,\Omega$ $L_d = 30\,\text{mH}$

SAF specifications

$L_f = 30\,\text{mH}$
$R_f = 1\,\text{ohm}$
$V_{dc} = 1000\,\text{volts}$
$V_{dc_{\text{ref}}} = 1000\,\text{volts}$
$C_{dc} = 4000\,\mu\text{F}$
$R_{dc} = 6000\,\text{ohms}$
$f_s = 100f\,\text{Hz}$
$T_s = 1/f_s\,\text{Hz}$

4.1. Simulation wave forms

1. Unbalanced current at source side
2. Non-linear Load voltage

3. Reference current

4. After compensation the load voltage

5. Voltage thd before compensation

6. Voltage thd after compensation

Table:-1

<table>
<thead>
<tr>
<th>Voltage thd</th>
<th>Before compensation</th>
<th>After compensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase-a</td>
<td>0.3213</td>
<td>0.0663</td>
</tr>
<tr>
<td>Phase-b</td>
<td>0.3536</td>
<td>0.0412</td>
</tr>
<tr>
<td>Phase-c</td>
<td>0.3298</td>
<td>0.0619</td>
</tr>
</tbody>
</table>

5. Conclusion

An important feature of this algorithm is that it is also applicable in the case of a combination of series and shunt active filter (series-shunt active filter) to generate reference compensation voltage and current. It is possible to completely eliminate the harmonics present in the voltage and current using a series-shunt active filter and, as such, there is no need for any optimization. However, optimization will be needed, if it is sufficient to limit the voltage and current harmonics to within a non-zero limit imposed by standards, instead of their complete elimination.

6. References

- S. George and V. Agarwal, “A novel technique for optimizing the harmonics and reactive power under non-sinusoidal supply and unbalanced load conditions,” in Proc. Power Electronics Specialist


