

# **The Influence of Nonlinear Loads on Optimal Operation Control of Electrical Distribution System**

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## **Abstract**

The main objective of power system operation is to supply the customer electricity demand with acceptable quality in an optimum way. With constantly varying demand, this objective may not be easily achieved. An adaptable system enhancement is therefore necessary to attain the objective. One of the strategies is controlling the switchable devices in distribution system for the purpose of maintaining the system voltage within the acceptable limits and minimizing the loss with minimum control action. One of the electricity customers is industrial institution, where some types of loads are nonlinear. This may include electrical machine and power electronic devices. Besides drawing the power from the grid, these loads may also inject distortion to the system causing destructive effects. This study proposes optimization scheme on distribution system considering the presence of nonlinear loads. In addition to control the system voltage and reduce the loss, system distortion should also be suppressed. To include the nonlinear loads into optimization, the calculation of power flow should be extended to accommodate the characteristic of nonlinear loads. The optimal control of switchable devices is determined using Genetic Algorithm (GA). The significant of involving distortion injected by nonlinear loads are highlighted.

## **Keywords**

Nonlinear loads, optimization, distortion,

## **1. Introduction**

Electric power utility includes components of generation, transmission and distribution. The components work together to fulfill the electricity demand of customer. It is the requirement of customer that the electricity should be supplied continuously with acceptable quality. From the side of electric power company the power should be generated and transferred in a minimum cost. The electricity demand that constantly changes may cause the difficulty of the utility to fulfill the demand with required quality. It is therefore necessary to control the system operation such that it may enable continuously fulfill the demand with acceptable quality. If this objective cannot be successfully achieved then either the electricity demand cannot be fully satisfied or the electricity supplied to the customer will be of poor quality.

Distribution system is part of power system taking important role in the entire system since this sub-system is directly connected and supplies the power to the customer. In the distribution system, variation of electricity demand is the problem, which is very difficult to overcome in technical and economical sense. If not carefully managed, the change of electricity demand may cause several problems such as voltage violation and power loss escalation. In order to solve these problems, an adaptable enhancement is therefore required for controlling the voltage and minimizing the power loss. Some modern distribution system may consist of some switchable devices such as Load Tap Changer (LTC) in the secondary side substation transformer, and shunt capacitors in the secondary side transformer and distribution feeders. These devices may be controlled for the purpose of maintaining the voltage not to exceed the permitted limits while minimizing the system power loss. This planning strategy practically consists of optimal dispatch of LTC and shunt capacitors for the aforementioned objectives. However, the devices may not be switched as many as needed, since it may reduce their lifetime. Therefore the dispatch control of the switchable devices must be carried out with minimum number of switching.

LTC is employed to regulate the substation secondary voltage to maintain the voltage at system buses close to the preset value under changing load conditions (Liang and Wang, 2003). However, controlling the voltage in this way does not significantly improve the voltage along the feeders, as this simply sets the secondary bus voltage. Load variation on feeders causes different voltage drop at different feeder. For this reason, shunt capacitors are installed on secondary side substation and feeders to provide reactive power compensation such that the voltage along the feeder may be further improved and the power losses can also be minimized. However, these capacitors need to be disconnected during light load conditions.

From the standpoint of devices control, the switching is performed to respond the load variation preserving the voltage profile and minimizing the loss. It is some kind of operation planning where the switching schedule should be determined in advance for the following 24-hour period. The switching number of the controlled devices may be confirmed from the planned schedule ensuring that the switching number does not exceed the maximum limit. As an operation planning, the electricity demand of the following day should be determined and it relies on load forecasting. Currently, there are some methods available for electricity load forecasting that enables providing reasonably accurate results.

The optimal dispatch of the controllable devices is an optimization problem. From the mathematical standpoint, this optimizes a specific objective function while satisfying the constraints. Practically, this determines the switching of LTC and shunt capacitors such that the loss is minimized and the voltage profile is improved while satisfying the constraints. It is evidently necessary to simultaneously control the switchable devices to achieve significant voltage profile improvement and power loss reduction. Unfortunately, comprehensive inclusion of the switched elements into dispatching problem leads to the very complicated optimization problem. The interdependence and interaction between the controllable devices result in problem complexity. The switching effects of shunt capacitors on secondary bus voltage may cause an LTC tap position to change, which forces LTC to operate too frequently. This interaction causes oscillations in the controllable devices resulting in reduction of device lifetime and higher maintenance cost. It is therefore desirable to achieve this optimization objective in the least possible number of control steps.

The extensive and ever increasing application of nonlinear loads has introduced a power quality problem. The so-called nonlinear load is the load that draws sinusoidal voltage but result in non-sinusoidal current causing nonlinear relation between voltage and current. The nonlinear current waveform can be decomposed into a number of sinusoidal waveforms with different frequencies and amplitudes. The waveform with power frequency is called as fundamental waveform while the waveforms with higher frequency are called harmonics. The presence of harmonic waveforms appending fundamental waveform causes distorted waveform. The distorted current spreading over the network causes voltage distortion. In some cases, the presence of harmonic is destructive in the forms of voltage amplification, losses addition and, if a resonance happens, it may destroy the equipment. Some type nonlinear loads are currently employed in industry such as electric motor and the associated speed drive and some power electronic devices. Harmonic has recently become a concern due to the application of these harmonic generating devices tends to increase.

The optimal control of distribution system operation is aimed to maintain the voltage profile with minimum losses. Due to the existence of harmonic distortion, the optimization should be extended taking the harmonics into account. Disregarding harmonics may cause the optimization providing operation planning unacceptable due to the possibility of uncontrolled voltage increment, losses magnification and, the most important effect of excessive harmonic distortion. Considering harmonics may lead the operation planning to not only controlling the voltage and losses but also suppressing the system distortion. The need of utilizing devices which are nonlinear will be no longer a problem as long as their impact on system is considered in operation planning. However, taking harmonic into account will further complicate the problem in hand, due to the analyses of power flow should be extended to some harmonic orders.

This paper proposes an operation planning of distribution system that includes a number of nonlinear loads. An optimization method based on evolutionary procedure is developed to determine the dispatch schedule of the controlled devices. The eligible schedules are evaluated using power flow analysis to provide system voltage profile and loss. For further harmonic inclusion, the power flow calculation should be extended to accommodate higher harmonic orders in the calculations. In addition to the results given by power flow, harmonic power flow also provides the level of system distortion. Therefore, optimization including harmonics enables confirming if excessive distortions take place and how they can be mitigated. To indicate the significant of harmonic inclusion, the optimization result generated by disregarding harmonics will be checked to detect if the system distortion takes place. It may also be highlighted that optimization considering load nonlinearity may simultaneously controlling the voltage, minimizing the loss, and mitigating the distortion.

## 2. Harmonic Power Flow

Power flow is the backbone of power system analysis and design. Power flow calculation generates results such as currents, voltages and power flowing at every bus in the specific system with particular condition. These information are essential for further analyses for instance to check the acceptance of voltage magnitudes and power losses. Power flow is formulated on the basis that power sources are the system generators and power “sinks” are the loads. For calculation purpose, network equation is formulated systematically in the node-voltage form. The formulation of the network equations in the nodal admittance form results in simultaneous complex linear algebraic equations in term of node currents. When node currents are specified, the set of linear equations can be solved for the node voltages.

Harmonic power flow is more general in that loads may be the “source” of harmonic energy (Semlyen and Shlash, 2000). The main source of system power is the generators but nonlinear loads connected to some buses may also inject the system sinusoidal waveforms higher frequency. For this reason, harmonic power flow may be developed by extending fundamental power flow with harmonic order components. The nature of the harmonic signals strongly depends on the type of nonlinear load. Therefore, nonlinear load modeling is crucial in harmonic power flow calculation due to its significant contribution to the accuracy of calculation results.

Nonlinear load modeling may be in the form of time domain and frequency domain. Time domain is based on transient-state analysis while frequency domain uses frequency-scan process to calculate the frequency response of a system. For harmonic sources which can be assumed as voltage-independent current sources, frequency domain model can be applied (Hong, Lin and Liu, 2000). They can be represented as frequency dependent elements with a harmonic admittance matrix representing their terminal behavior for a given harmonic order. Frequency domain approach for harmonic analysis is proposed in this study.

The method for the harmonic power flow calculation is generally classified into couple and decouple. The main difference of the methods is the consideration of coupling between harmonics. The couple approach considers the couple among of harmonic orders, while the coupling is omitted in decouple approach. This study proposes decouple approach for harmonic power flow calculation due to the affordable computation and acceptable accuracy. Furthermore, this approach uses nonlinear load model in the form of magnitude and angle of injection current at harmonic orders that can be easily obtained from measurement.

For harmonic power flow calculation, the system at higher frequencies is modeled as the combination of passive elements and current sources. The generalized model is suggested for linear loads, which is composed of resistance in parallel with an inductance selected to account for the respective active and reactive power at fundamental frequency. Nonlinear loads are considered as ideal harmonic current sources that generate harmonic currents and inject them into systems (Yu, Xiong and Wu, 2004). The admittance-matrix-based harmonic power flow is the most widely used method for distribution systems because it is based on the frequency-scan process (Teng and Chang, 2003). In this approach, admittance matrix of system components needs to be modified according to the harmonic order. If skin effect is ignored at higher frequencies, the resulting  $h$ th harmonic frequency load admittances, shunt capacitor admittances and feeder admittances are given, respectively, by:

$$y_{li}^n = \frac{P_{li}}{|V_i^1|^2} - j \frac{Q_{li}}{h|V_i^1|^2} \quad (1)$$

$$y_{ci}^n = h y_{ci}^n \quad (2)$$

$$y_{i,i+1}^n = \frac{1}{R_{i,i+1} + jhX_{i,i+1}} \quad (3)$$

where  $P_{li}$  and  $Q_{li}$  are the respective linear active and reactive load at bus  $i$ . The fundamental and the  $h$ th harmonic current of the nonlinear load installed at bus  $i$  with real power  $P$  and reactive power  $Q$  are modeled as:

$$I^{(1)} = \left[ (P_i + jQ_i) / V^{(1)} \right]^* \quad (4)$$

$$I^{(h)} = C(h) I^{(1)} \quad (5)$$

where  $C(h)$  is the ratio of the  $h$ th harmonic current to its fundamental. The harmonic voltages are computed by solving the following load flow equation:

$$Y^{(h)} V^{(h)} = I^{(h)} \quad (6)$$

The *rms* voltage at bus  $i$ , is defined as:

$$V_{irms} = \left( \sum_{h=1}^H |V_i^{(h)}|^2 \right)^{1/2} \quad (7)$$

and the related total harmonic distortion of voltage ( $THD_{vi}$ ) is:

$$THD_{vi} = \frac{\left( \sum_{h \neq 1}^H |V_i^{(h)}|^2 \right)^{1/2}}{|V_i^{(1)}|} \times 100\% \quad (8)$$

where  $H$  is the highest harmonic order considered. At the  $h^{\text{th}}$  harmonic frequency, power loss in the line section between bus  $i$  and  $i+1$  is:

$$P_{loss(i,i+1)}^h = R_{i,i+1} \left( |V_{i,i+1}^{(h)} - V_i^{(h)}| |y_{i,i+1}^{(h)}| \right)^2 \quad (9)$$

and the total power loss, including losses at harmonic frequencies, for an  $m$  bus system is:

$$P_{loss} = \sum_{h=1}^H \left( \sum_{i=1}^{m-1} P_{loss(i,i+1)}^h \right) \quad (10)$$

The flowchart of harmonic power flow using decouple approach is shown in Fig. 1.

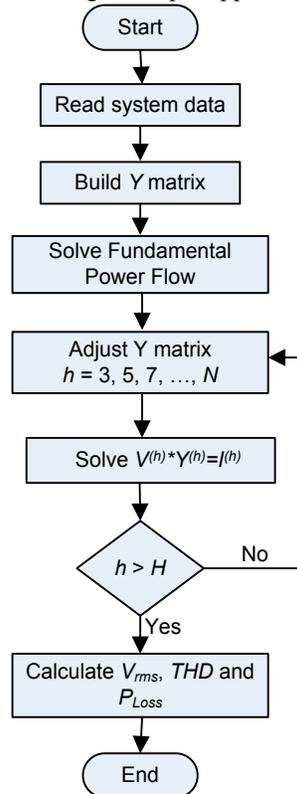


Figure 1. Flowchart of harmonic power flow calculation using decouple approach

The accuracy of harmonic power flow will determine to the precision of analyses and therefore the developed program is benchmarked with ETAP software package and the HARMFLOW algorithm. The distorted IEEE 18-bus system is used to compare the accuracy of the developed program and with those generated by ETAP and HARMFLOW (Masoum *et al.*, 2004). This system consists of a 3 MW six-pulse converter, which is modeled as harmonic current sources. Simulation results are compared in Table 1 and indicate the fine accuracy of the developed calculation for harmonic power flow (Ulinuha, Masoum and Islam, 2006).

Table 1. Result comparison with ETAP and HARMFLO

Simulation Results	Average deviation (%) with	
	HARMFLOW	ETAP
Fundamental Voltage	0.005870	0.002134
<i>rms</i> Voltage	0.027797	0.026716
Distortion Factor	0.000327	0.000267
THD of Voltage	0.572418	0.499733

### 3. Problem Description and Proposed Solution

The objective function of optimal distribution system control by dispatching the switchable devices is minimization of energy loss over a 24-hour period, as given the following equation.

$$\min \sum_{t=1}^{24} P_{loss}(Q_t, T_t) * \Delta t \quad (11)$$

where  $P_{loss}$  is the total power loss at hour  $t$  as a function of  $Q_t$  and  $T_t$  that are the status of shunt capacitors and tap position of LTC, respectively. While,  $\Delta t$  is time interval that is normally taken as 1 hour. This objective function is subjected to the following constraints including THD limits to control harmonic distortion.

- Voltage constraint

$$V_{i \min} \leq V_{irms} \leq V_{i \max} \quad (12)$$

where  $V_{i \min}$  and  $V_{i \max}$  are the minimum and maximum limits of *rms* voltage at bus  $i$  ( $V_{irms}$ ), respectively.

- Total harmonic distortion of voltage ( $THD_v$ )

$$THD_{vi} \leq THD_v^{\max} \quad (13)$$

where  $THD_{vi}$  and  $THD_v^{\max}$  are the distortion of voltage at bus  $i$  and the maximum allowable voltage distortion, respectively.

- Maximum switching operations of LTC

$$\sum_{t=1}^{24} |TAP_t - TAP_{t-1}| \leq K_T \quad (14)$$

where  $TAP_t$  and  $K_T$  are LTC tap position at hour  $t$  and the maximum limit of LTC daily switching, respectively.

- Maximum switching operations of shunt capacitors

$$\sum_{t=1}^{24} (C_{nt} \oplus C_{nt-1}) \leq K_c; \quad n = 1, 2, \dots, nc \quad (15)$$

where  $C_{nt}$  and  $K_c$  are the status of capacitor  $n$  at hour  $t$  and the maximum limit of capacitor switching, respectively. While  $nc$  is the number of shunt capacitors.

For the problem of optimal dispatch of LTC and shunt capacitor, the interdependence between bus voltages and capacitor settings makes the optimization problem quite complicated requiring simultaneous dispatch of the controlled elements (Ulinuha, Masoum and Islam, 2011). To effectively satisfy the maximum allowable number of LTC switching, the daily load curve will be divided into several intervals using a GA (Hu *et al.*, 2003). Another GA is also proposed to determine the optimal control of LTC and shunt capacitors under harmonically distorted situations. Besides its general features, GA is selected due mainly to its encoding ability that enables to comprehensively consider the simultaneous dispatch of the controlled devices and to check the switching constraints before performing unnecessary calculations.

#### 3.1 Division of Load Interval

The idea of load interval division is based on the reality that several apparent load levels exist during a day. These intervals may be used to determine the position of LTC tap that remains constant during a load interval and may differ at a different load interval. A typical daily load curve (Shenkman, 1990) is shown in Fig. 2 and will be used in this paper. The load curve indicates some intervals where the load variations are fairly small and if they can be determined, the schedule of LTC tap position can be effectively decided. This will not only take into account the overall daily load change, but also easily satisfy the LTC switching constraint. With an accurate load forecasting in hand, the LTC dispatch obtained in this way can be implemented with confidence. Modern load forecasting techniques are currently available providing highly accurate forecasts (Amjady, 2007).

In order to determine the optimal load intervals, the number of interval is initially assumed. A genetic algorithm is then employed to determine the beginning and the end of each interval. The possible interval combinations are represented as chromosomes consisting of some binary substrings and may be constructed using the following approach:

0101	0011	...	0010	← The chromosome
5	3	...	2	← The substring value
1 <sup>st</sup>	2 <sup>nd</sup>	...	n <sup>th</sup>	← The $n$ intervals

Every chromosome consists of some binary substrings according to the number of interval considered. Every substring corresponds to the value indicating the length of an interval. The sum of all substring values indicates the

total length of the entire interval, which is 24 hours. The chromosomes are then evaluated using the following fitness function:

$$F = F_{\max} - \min \sum_{l=1}^n \sum_{t=1}^{l_i} [(P_{tl} - PA_l)^2 + (Q_{tl} - QA_l)^2] \quad (16)$$

Subject to

$$\sum_{l=1}^n l_i = 24 \quad (17)$$

where,  $F_{\max}$  is constant that converts fitness function to the standard form,  $P_{tl}$  and  $Q_{tl}$  are active and reactive powers (at hour  $t$  and load interval  $l$ ),  $PA_l$  and  $QA_l$  are average active and reactive powers (at load interval  $l$ ),  $T$  is number of hour at  $l^{\text{th}}$  load interval, and  $L$  is number of interval assumed. The best chromosome at the end of generation represents the best interval combination and will be used for further calculation.

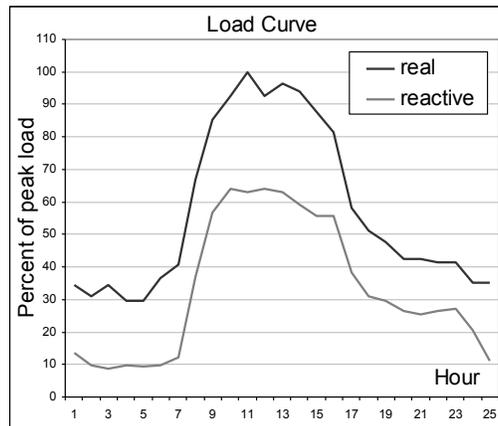


Figure 2. A typical daily load curve

### 3.2 Optimal distribution system control

With the load intervals in hand, the possible LTC tap position at every hour in a day can be determined following the previously given interval. The tap position at an interval is maintained to be constant but may differ at the different interval. It is assumed in this paper, that the difference between the consecutive LTC tap positions is no greater than 15. Therefore, the chromosome with substring of 4 bits is used in this matter. The eligible chromosome is therefore that, which has the sum of substring value no more than the maximum allowable LTC switching operation. This is to assure that the LTC will not move more than switching limit. The chromosome for LTC tap scheduling may be constructed as follows:

0101	0110	...	1010	← The chromosome
5	6	...	10	← The substring value
1 <sup>st</sup>	2 <sup>nd</sup>	...	n <sup>th</sup>	← The $n$ intervals

For shunt capacitors at substation, their switching operation is limited by a particular maximum number. Therefore, the chromosome that represents the switching schedule for these shunt capacitors consists of several substrings where, every substring denotes a 24-hour switching status for every shunt capacitor. If the  $t^{\text{th}}$  bit is 0, the status of the related shunt capacitor at hour  $t$  is “off”. Therefore, the length of every substring is 24 bits and the length of chromosome for  $sc$  shunt capacitors is  $sc \times 24$  bits. The chromosome is eligible if the switching number in every substring is no more than the maximum switching limit.

The shunt capacitors installed at distribution feeders are normally allowed to be switched “on” and “off” once a day. Therefore, it may be simply required to determine the time for switching the capacitor “on”, and the duration for keeping it “on”. The substring that represents the schedule for every shunt capacitor can be formed where the first segment represents the switch on time and the remaining represents the “on” duration. As the latest time to switch it on or the maximum “on” duration is the hour of 24, a segment of 5 bits is used and, therefore, the length of substring is 10 bits. For the following example of a substring:

00100	01101	← The substring
4	13	← The segment value
1 <sup>st</sup>	2 <sup>nd</sup>	← The segment

The associated actual schedule is 000111111111111100000000.

The eligible substring is that, which has total segment value of no more than 24. The qualified chromosome can only be formed by the eligible substrings. Constructing the chromosomes in this way will greatly reduce its length, particularly for the system with a large number of feeder shunt capacitors.

A complete eligible chromosome representing 24-hour devices scheduling is consecutively constructed by the eligible chromosome for LTC, substation shunt capacitors, and feeder shunt capacitors. Assessment of every chromosome requires running the harmonic power flow for 24 times. The number of chromosome implies the wide of solution area to consider. The more chromosome to be included in optimization, the higher possibility of achieving better solution. However, the bigger number of chromosome may lead the computation to be very intense. The assessment for each chromosome is carried out by confirming the fulfillment of the optimization objective, represented by the following fitness function:

$$F = \max \left[ F_{\max} - \left( w_{loss} \sum_{t=1}^{24} loss_t + w_V \sum_{t=1}^{24} \sum_{i=1}^I \Delta V_{it} + w_{THD} \sum_{t=1}^{24} \sum_{i=1}^I \Delta THD_{it} \right) \right] \quad (18)$$

where  $loss_t$  is the per-unit real power loss at hour  $t$ ,  $\Delta V_{it}$  is the per-unit *rms* voltage violation at bus  $i$  at hour  $t$ , and  $\Delta THD_{it}$  is the per-unit THD violation at bus  $i$  at hour  $t$ . While  $w_{loss}$ ,  $w_V$  and  $w_{THD}$  denote the weighting coefficients of real power loss, *rms* voltage violation, and THD violation, respectively. For optimal system control disregarding nonlinear load, the term of THD control is omitted.

### 3.3. Evolutionary Strategy of the Genetic Algorithms

The initial chromosomes are randomly generated and selected for constructing the initial population. The selected chromosomes are those, which satisfy the switching constraints. The selection of parents for crossover uses tournament method and the children are generated by one-point crossover from their parents (Michalewics, 1996). The probability of crossover and mutation are fixed throughout the generation as well as the weighting functions. The detail of optimization parameters is given in Table 2.

Table 2. Optimization Parameter for GA in this paper

Parameter	Value
Population size	30
Load level*	4
Maximum generation	50
Probability of crossover	60 %
Probability of mutation	1%
Convergence tolerance**	$1 \times 10^{-6}$
Maximum switching of LTC	30 tap displacements per day
Maximum switching of substation capacitor	6 times per day
Maximum switching of feeder capacitor	2 times per day
Deviation of bus voltage	0.95 – 1.05 p.u.
THD limit of bus voltage	5 %
Weighting coefficient (Eq. 18) ***	
Disregarding nonlinear load effects	
Voltage ( $w_V$ )	0.670
Power loss ( $w_{loss}$ )	0.330
Considering nonlinear load effects	
Voltage ( $w_V$ )	0.428
Power loss ( $w_{loss}$ )	0.286
THD ( $w_{THD}$ )	0.286

\*) Determines the number of interval of the partitioned load

\*\*) The deviation of the successive fitness values used to terminate the iterations

\*\*\*) Indicates the importance level of one objective with respect to the other objectives or constraints

The size of population is fixed during the calculation and the best chromosome in every generation is saved and directly transferred to the next generation. The algorithm converges if the iteration reaches the maximum generation number. However, the developed algorithm is devised by a procedure that detects premature convergence by checking the improvement of fitness after the iteration reaches the middle of generation. The algorithm will terminate if there is no improvement after few iterations. The flowchart of optimization problem using GA is shown in Fig. 3.

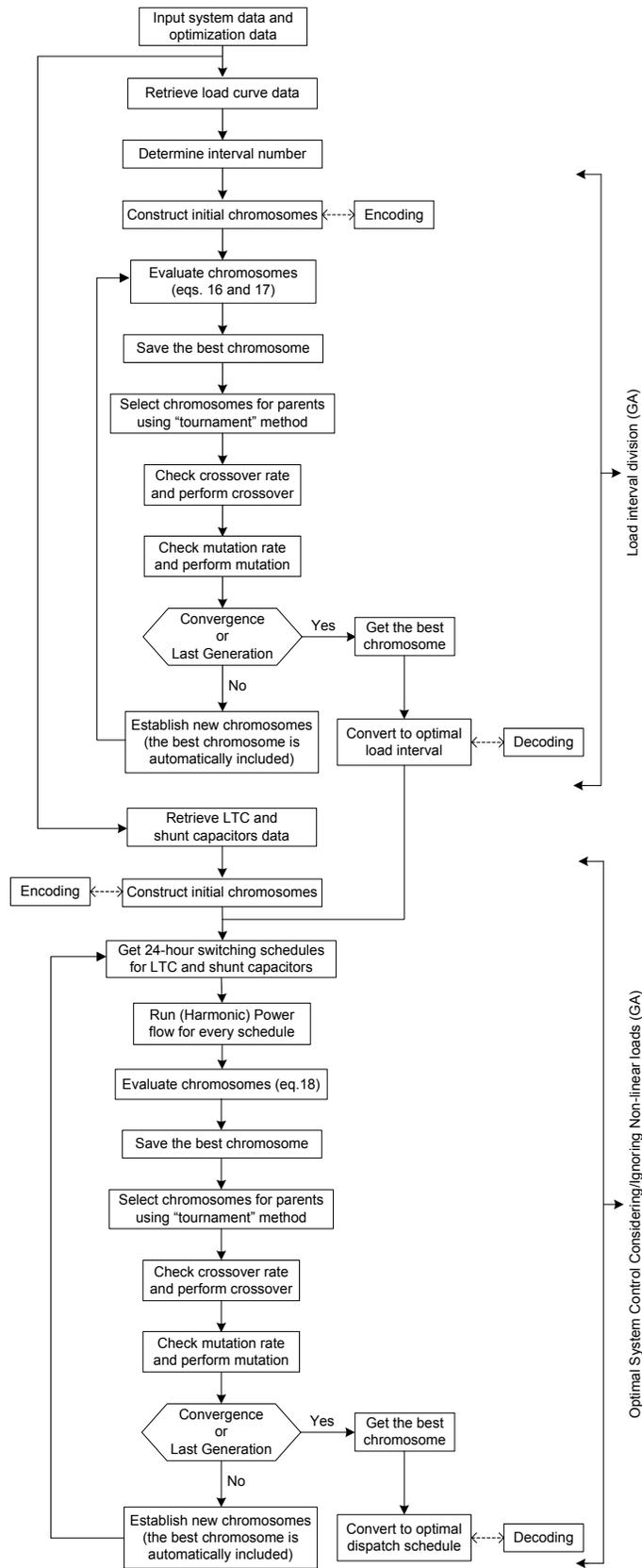


Figure 3. Flowchart of optimal system control considering/disregarding nonlinear loads

## 4. Results and Discussion

### 4.1 System Data

The 30-bus distribution is used in this study for simulations (Hu *et al.*, 2003). The system includes 7 nonlinear loads and devised with LTC, 2 shunt capacitors in secondary side transformer and 5 shunt capacitors in feeders (Fig. 4). The peak of both real and reactive loads are from (Grainger and Civanlar, 1985) and these loads are assumed to change according to the curve indicated in Fig. 2. As the load model has a great influence on the power flow results, this study models the load at each bus consisting of 50% constant impedance and 50% constant power. The data of shunt capacitors and nonlinear loads are given in Table 3 and Table 4, respectively. The LTC may be controlled to move over 17 tap positions from position +8 to -8 resulting in adjustment of voltage at secondary side substation transformer from +5% to -5% with respect to the nominal voltage.

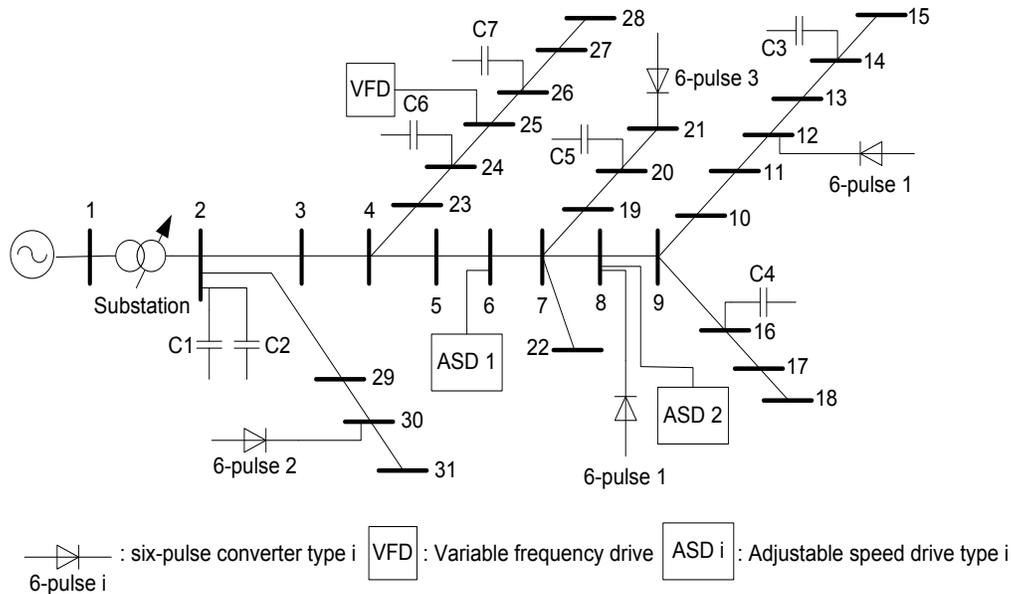


Figure 4. The 30-bus distribution system serving nonlinear loads.

Table 3. Capacitor Data for Distribution System

Capacitor	C1	C2	C3	C4	C5	C6	C7
Bus Location	2	2	14	16	20	24	26
Size (kVAR)	900	600	600	600	300	900	900

Table 4. Nonlinear load data for 30-bus distribution system

Nonlinear Bus	Nonlinear Load Type	kW	kVAr
6	PWM adjustable speed drive 2	575	326
8	six-pulse 2	436	231
8	PWM adjustable speed drive 1	247	158
12	six-pulse 1	347	176
21	six-pulse 3	315	156
25	six-pulse variable frequency drive	454	229
30	six-pulse 2	527	242

### 4.2 Optimization Results

The system is run by considering and disregarding nonlinear loads. To exclude the effect of nonlinear loads, the injection currents at higher frequency are not taken into account. For further considering the influence of nonlinear loads, the system is optimized by including the higher frequency components of injection currents. The optimal scheduling of the controllable devices is given in Table 5. It may be inspected from the generated optimal schedules that the switching constraints are fulfilled. However, as expected, different schedule is given by optimization ignoring and considering distortion effects of nonlinear loads.

Table 5. The optimal schedules of controllable devices ignoring/considering nonlinear loads effect

Hour	Ignoring nonlinear loads effect							Considering nonlinear loads effect								
	LTC	C1	C2	C3	C4	C4	C6	C7	LTC	C1	C2	C3	C4	C4	C6	C7
1	4	0	0	0	0	0	0	0	3	1	0	0	0	0	0	0
2	4	0	0	0	0	0	0	0	3	0	0	0	1	0	0	0
3	4	0	0	0	1	0	0	0	3	0	0	0	1	0	0	0
4	3	0	1	0	1	0	0	0	3	0	0	0	1	0	0	0
5	3	0	0	0	1	0	1	0	3	1	0	0	1	0	0	0
6	3	0	1	0	1	0	1	0	3	1	0	0	1	0	0	0
7	3	0	1	0	1	1	1	0	3	1	0	0	1	1	0	0
8	4	0	1	1	1	1	1	0	3	1	0	1	1	1	0	0
9	4	1	1	1	1	1	1	1	5	1	0	1	1	1	0	1
10	4	1	1	1	1	1	1	1	5	1	0	1	1	1	0	1
11	4	1	1	1	1	1	1	1	5	1	0	1	1	1	1	1
12	4	1	1	1	1	1	1	1	5	1	0	1	1	1	1	1
13	4	1	1	1	1	1	1	1	5	1	0	1	1	1	1	1
14	4	1	0	1	1	1	1	1	5	1	1	1	1	1	1	1
15	4	1	0	1	1	1	1	1	5	1	0	1	1	1	1	1
16	4	0	0	1	1	1	1	1	5	1	0	1	1	1	1	0
17	4	0	0	1	1	1	1	1	5	0	0	1	0	0	1	0
18	4	0	0	1	1	0	0	1	3	0	1	1	0	0	1	0
19	4	0	0	1	1	0	0	0	3	1	0	1	0	0	1	0
20	4	1	1	1	1	0	0	0	3	1	1	1	0	0	1	0
21	4	0	1	1	1	0	0	0	3	1	1	1	0	0	1	0
22	4	0	1	1	1	0	0	0	4	1	1	1	0	0	0	0
23	4	0	1	0	1	0	0	0	4	0	1	0	0	0	0	0
24	4	1	1	0	0	0	0	0	4	1	0	0	0	0	0	0

To highlight the significance of taking nonlinear loads effects into account, the generated schedule ignoring higher frequency injection currents is operated in the system serving nonlinear loads. The implementation of this schedule leads the system to encounter some overvoltage problems at some buses for some hours. Voltages at bus 1 and bus 2 are detected violating the limit most frequently. Therefore, the hourly voltages of these buses are investigated. The hourly maximum voltage of the system is also checked for more illustration. The hourly maximum voltage and the voltages of bus 1 and bus 2 are displayed in Fig. 5.

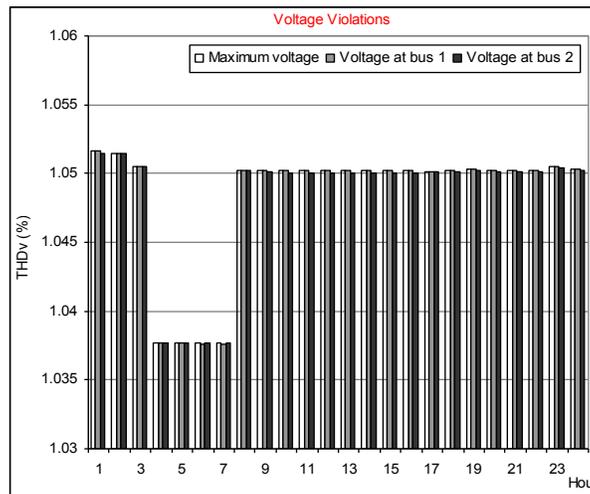


Figure 5. System overvoltage due to implementation of schedule ignoring nonlinear loads effect

On the other hand, it is also observed excessive system distortion due to application of optimal schedule ignoring nonlinear loads effect for the system serving nonlinear loads. The hourly maximum THD is shown in Fig. 6 indicating maximum limit violations at hour 1 and hour 2. Further observation of the implementation result indicates that at hour 1 and hour 2 all buses have distortion level higher than the maximum allowable limits of 5 %. The distortion levels at the hours are indicated in Fig. 7.

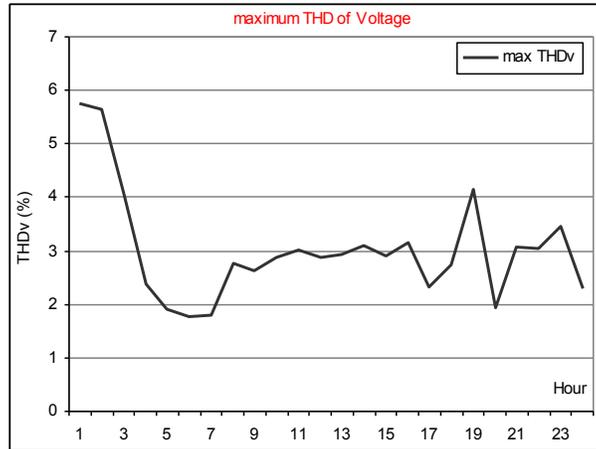


Figure 6. The hourly maximum distortion level due to implementation of schedule ignoring nonlinear loads effect

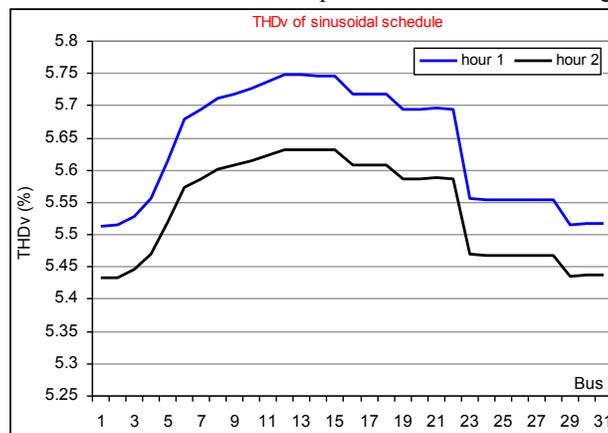


Figure 7. The distortion level at hour 1 and 2 due to implementation of schedule ignoring nonlinear loads effect

It may be verified that implementation of schedules given by ignoring nonlinear loads for system serving nonlinear loads is unacceptable as it may cause violations on voltage and excessive system distortion. It justifies the necessary of including the effect of nonlinear loads in the optimal system control. The excessive system distortion is obviously destructive for the system equipments and to the connected loads. The overvoltage problems are mainly because voltage amplifications due to higher frequency injection currents have not been considered. As nonlinear loads are extensively applied in distribution system, taking them into optimal dispatch problems is necessary.

The significance of including nonlinear load effects is further investigated in term of optimization benefits. Considering the effects in the optimal dispatch problems may generate different schedule and result in different optimization benefits (Zobaa and Aziz, 2004). Comparison of the optimization benefits achieved by disregarding and considering nonlinear loads effect demonstrates that the latter does not only assure the satisfaction of voltage and THD constraints but also leads the system to achieve higher optimization benefits. The comparisons are presented in Table 6.

Table 6. Comparison of optimization benefits due to ignoring/considering nonlinear loads effect

Optimization Benefits	Ignoring nonlinear loads effect	Considering nonlinear loads effect
Energy Saving (MWh)	265.78	278.16
Average Voltage improvement (%)	5.81	7.49
Average Distortion Reduction (%)	3.5	3.2

#### 4. Conclusion

The optimal control of distribution system is investigated due to the presence of nonlinear loads. The main conclusions are:

- The optimal control of distribution system may be carried out by switching the LTC and shunt capacitors,
- Comprehensive device control may be simultaneously determined using Genetic Algorithm,
- The purpose of including nonlinear loads on optimal dispatch problem is to assure the system distortion does not exceed the maximum allowable limit,
- Straightforwardly taking the effects of nonlinear loads into account enables achieving higher energy saving and better average voltage improvement.

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#### Biographies

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