Smart Electric Grids Three-Phase Automatic Load Balancing Applications using Genetic Algorithms

A. Gouda*, A. Abul-Farag**, H. Mostafa*** and Y. Gaber ****

***Abstract*- Smart Electrical Grids require nowadays a large interest in the electrical load distribution balancing problem. This problem is a well known for not having an optimal solution for large-scale systems, where the number of single phase consumers connected to three phase systems increases especially in very large-scale electrical distribution systems. This paper presents a new control technique for an automatic circuit phase change as well as an optimisation approach using Genetic Algorithms (GA) used to enhance the solution of electrical load distribution balancing problem. In the first part of the paper, the system under study is introduced, as well as the various solutions adopted. In the second part of the paper, a GA formulation and implementation of the solution is presented. The efficiency of the GA solution is also discussed.**

***Keywords:*- Smart Electric Grids, Genetic Algorithms, Electric Load Balancing.**

I. INTRODUCTION

Most domestic supplies at households and semi-industrial premises are supplied from single-phase AC with a phase and neutral wire. However, most electricity is generated and transmitted as three-phase AC. Rather than having a single coil rotating in a magnetic field, three-phase generators have three coils fixed at 120° from each other; thus three voltages, that are 120° out of phase with each other, are produced in three separate circuits. The phases are normally called red (R), yellow (Y) and blue (B). Using three phases is a standard issue nowadays due to the numerous known reasons from power constancy, copper wire utilisability, zero neutral currents for balanced systems, etc … [1].

Over time, distribution feeders have a tendency to increase in load unbalance due to [1-4]:

1. Loads on single-phase lines gradually increase.
2. Single-phase lines arbitrarily get manually switched to other phases.
3. Unequal distribution of single phase loads on three-phase lines.
4. Lack of planning.
5. Asymmetrical transmission impedances (due to untransposed lines).
6. Asymmetrical transformer winding impedances.
7. Blown fuses on phases of capacitor banks.
8. Unbalanced three-phase loads, such as arc furnaces.

The results are [1-4]:

1. Voltage phase shifts deviating form the 120°.
2. Increased return currents in the neutral conductor.
3. Increased losses due to excessive unnecessary currents.
4. Physical ramifications of the connections.
5. The unbalance in current creates a neutral point voltage shift.
6. Over-voltages and under-voltages occurring at different points of the feeder.
7. Unbalance in current dictated by placement of load on feeders.

The smart grids are nowadays targeted everywhere in three phase electrical power systems of modern countries. The various problems arising with electrical power distribution grids arise from the fact that consumer loads are not perfectly predictable and do not balance out when different loads are distributed over the three phases [1].

This in effect renders the distribution problem of the loads on the corresponding phases rather difficult in order to reach the case of balanced loads. The proper choice of which loads gets connected to which one of the three phases is in effect very important in order to render the neutral conductor current to minimum [2,3]. The problem then simplifies to an ordinary constrained optimisation problem which can be solved by several techniques.

The proposed solution in this paper treats the phase unbalance and the large value of neutral conductor current. Subsequently all over- and/or under-voltage problems are then greatly reduced. It is to be noted that no consideration was given to the feeder impedances in the work presented herein as this is outside the scope of this paper.

II. THREE-PHASE LOAD BALANCING TECHNIQUES

The first and most basic solution is the use of special transformers, such as "Scott" and "Steinmetz" transformers [1]. In such cases, the three-phase grid sees a balanced load resulting from the single phase loads connected to the transformers. This is a rather expensive solution which increases to a great extent the initial installation cost of the system.

Another type of mitigation technique is to rearrange or redistribute the loads in such a way that the system becomes more balanced. For certain applications, there is a possibility of reducing unbalance by changing the operating parameters such as

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the line and short circuit impedances of the system at the point of connection [1-4].

Classically the selection problem of which load is to be connected to which phase was treated manually by anticipating the average amount of current magnitude. No consideration for the respective load power factors was taken into consideration. The change of phase was then performed manually per load across the terminal wiring [1]. The problem in this case lies within the constraints of load disconnection and the following change of phase.

Another solution technique makes use of the fast-acting power electronic circuits, such as 'Static-VAR-Compensators', which can be configured to limit the unbalance [1-4]. These behave as if they were rapidly changing complementary impedances, compensating for changes in impedance of the loads on each phase. They are also capable of compensating unwanted reactive power. However, these are expensive devices, and are only used for large power loads when other solutions are insufficient.

Finally another method making use of three single phase contactors each connected to a different phase (R, Y and B) solves the problem at a fraction of the expense of the other previous techniques [1-4]. Figure 1 shows the connection of the three contactors with the three phase supply and the single phase load. Very good care must be taken in order to ensure that only one contactor is allowed to close its contacts at a time; otherwise a line to line electrical short circuit would occur.

The optimisation techniques for such circuits ranged from fuzzy logic, genetic algorithms, and several other heuristic techniques [2-4].

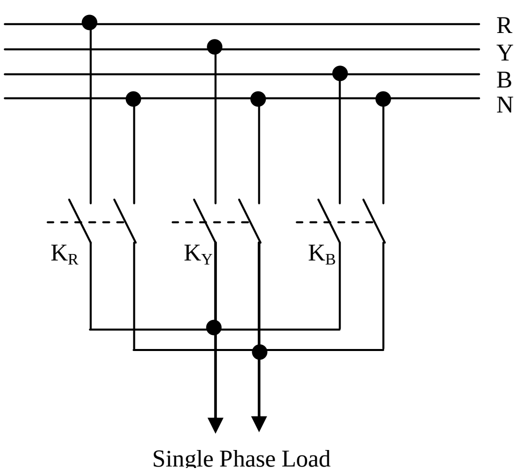

Figure 1: Three-Contactor Method

III. Three-Phase Automatic Phase Change Techniques

Figure 2 shows a proposed networked system capable of implementing the process presented in Figure 1 automatically and dynamically during the normal system operation. Three different loads are shown in the figure. For each of these load systems, a measuring device computes the load current and its corresponding power factor (*pf*) angle and transmits these readings from the slave unit through the communication network bus (using RS-485) to the master unit. This data is then processed by the central computing device (Industrial PC) which can be connected through the internet to the electricity distribution company. The central PC collects the data from all the loads under its control. It is then responsible for deciding which load is to be connected to which one of the three phases according to the optimisation technique implemented in its software. The decision for each load is then sent back from the master unit to each one of the corresponding slave units at the corresponding loads. Note that this system may include a UPS in order to eliminate the switching transient from the load supply during the transition from one phase to the other. This is of course dependent upon the importance of the load and its sensitivity to voltage interruptions. The details of the system description are outside the scope of this paper.

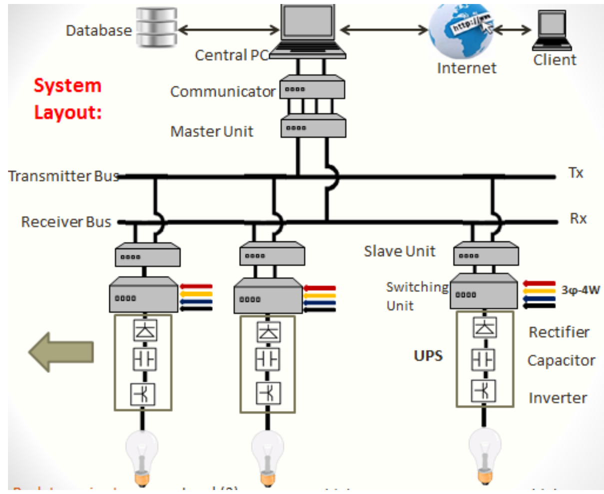

Figure 2: Automatic Phase changing system under consideration

The advantages of the automatic system presented in Figure 2 for the smart load balancing problem:-

1. Provides an up-to-date balanced operation of three-phase systems by continuous metering of individual single-phase loads.
2. Helps to continuously avoid unbalance problems and losses.
3. Easy to install on any system with almost no significant changes in the distribution system.
4. Allows the user to monitor the load current and its phase angle at any time.
5. Allows the central computer to monitor all the individual single-phase loads at any time.
6. Allows the central computer to generate an alarm when there exists a fault in any single-phase load.
7. Provides a database for the historical values of each load at the central PC.
8. Provides a remote monitoring of the system status and history using a web interface.
9. Power factor correction can be achieved by connecting lag power factor loads with lead power factor loads on the same phase.
10. The harmonic content can be reduced by the concept of useful harmonics; negative harmonics with positive harmonics on the same phase eliminate each other.

It is to be noted that only the load balancing technique is to be considered in this paper.

IV. OBJECTIVE FUNCTION FORMULATION

The main task of applying any solution to the system relies on the formulation of the problem. It is important in this case to address the problem formulation.

The first task is to identify the control variable. In this case it is the balancing of phase loads in order to reduce the neutral current to minimum. This in effect is adopted under the consideration that the interconnecting electrical cable line impedances are neglected due to the fact that such loads are so close to each other as in the case of commercial or residential building blocks where the distances and hence the cable lengths between each two consecutive consumer loads are very small.

The currents magnitude of load k is given by I_k at each node (load) as well as its corresponding power factor angle (φ_k). This current in phasor format will be added to the total current of each phase depending upon its corresponding connection. The three total phase currents ($\overline{I}_{tot}^{A}$, $\overline{I}_{tot}^{B}$ and $\overline{I}_{tot}^{C}$) are given by

$$\overline{I}_{tot}^{A} = \sum_{k=1}^{N_{ld}} A_k \cdot \overline{I}_k \tag{1}$$

$$\overline{I}_{tot}^{B} = \sum_{k=1}^{N_{ld}} B_k \cdot \overline{I}_k \cdot a \tag{2}$$

$$\overline{I}_{tot}^{C} = \sum_{k=1}^{N_{ld}} C_k \cdot \overline{I}_k \cdot a^2 \tag{3}$$

where, $a = 1\ \angle 120^{\circ}$ and A_k, B_k and C_k are three binary variables (0 or 1) corresponding to the whether the corresponding load current at node k is connected (value = 1) or not connected (value = 0) to that particular phase. The values of a and a^2 are only considered here to compensate for the 120 ° and 240° phase shifts between phases A, B and C. It is to be noted that the quantities in equations 1 to 3 are phasor quantities added vectorially with respect to each other in order to preserve the phase angles of each load with respect to its corresponding phase voltage.

In order to reach the balanced loading condition, the neutral current is given by the equation:

$$\overline{I}_N = \overline{I}_{tot}^{A} + \overline{I}_{tot}^{B} + \overline{I}_{tot}^{C} \tag{4}$$

In equation (4), only the total neutral current of all loads is considered for the optimisation. The optimisation (in this case a minimisation of I_N) is subject to the constraint that it should only consider moving each load as a whole from one phase to another in determining the optimal distribution of the load currents across the three phases of the electric feeder. Another constraint applied to the system is that the three phases should be loaded almost equally; i.e., the current magnitudes in the three phases must be almost equal to within a certain percentage of unbalance determined by the operator of the electric power system.

V. GA SOLUTION APPROACH

In order to implement a GA [5-7] solution for the above optimisation problem it is required to clearly identify the following definitions:

A. Gene

The implementation of the gene (k) in this modelling includes three parts:

- Load current magnitude at node k given by I_k.
- Load current phase angle at node k given by φ_k.
- Phase at which this particular node is to be connected (1, 2 or 3) corresponding to phases (R, Y or B).

The first two values of the gene are fixed during the whole optimisation problem since it includes the original system data. The only variable that is allowed to change is the phase connection of each gene. The following table shows the values of the phase connection and the corresponding values of A_k, B_k and C_k.

Phase	A_k	B_k	C_k
1	1	0	0
2	0	1	0
3	0	0	1

B. Chromosome

The chromosome includes a number of genes equal to the total number of loads in the electrical power system (N_{ld}). The chromosome will include its own solution for the phase selection of each of the loads at the different nodes.

C. Population

The population of the genetic algorithm system is the collection of valid chromosomes with a total number of N_{chr}. Each element in the population has to have its fitness evaluated. The population is then sorted in ascending order according to the fitness of each chromosome since this is a minimisation problem as discussed in the previous section. The crossover and mutation operators are applied to the chromosomes to generate new off-springs. The cycle then repeats until stabilisation or a maximum number of generations (N_G) is reached.

D. Fitness function and chromosome validity

The fitness of each of the chromosomes of the population is to be evaluated using a fitness function given by

$$Minimise \quad \{I_N\} \qquad \text{Subject to}$$

$$If \begin{cases} difference(I_{tot}^{A}, I_{tot}^{B}, I_{tot}^{C}) > Tolerence & fitness = 10^6 \\ otherwise & fitness = I_N \end{cases} \tag{5}$$

The fitness function described herein ensures the elimination of the chromosomes which do not satisfy the conditions discussed in the previous section by assigning very large values to the non-valid ones.

E. GA operators

Cross-over is applied to each pair of the chromosomes in order to generate the new off-springs subject to the constraints. This is effectuated onto a certain percentage of the chromosomes. The remaining chromosomes are subjected to mutation. A basic roulette randomisation technique selection mechanism is adopted in order to decide the point of crossover or mutation application at a certain gene. It is worthwhile to iterate here that the changes resulting from the two above operators are only applied to whole genes.

VI. Results and Discussion

The GA program was applied to a system of N_{ld} = 100 nodes. The population size was chosen to be N_{chr} = 50 chromosomes. The system was allowed to run for a maximum of N_G = 50 generations or until a certain minima is reached. The crossover is effectuated onto 80% of the population and the mutation is performed on the remaining 20%. Figure 3 shows a typical fitness variation curve against the generation number.

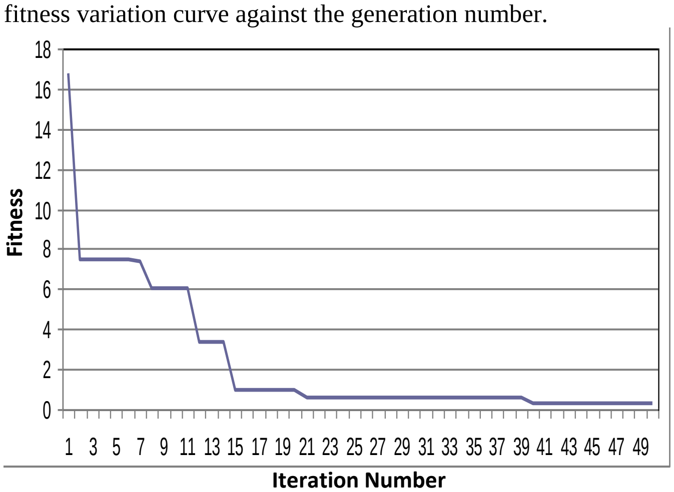

Figure 3: Fitness Variation Curve

Table 1:Fitness Comparison for 8different loading conditions

Iteration	Generation No.	Best Fitness	Total Phase Current	%error
1	25	0.6967	307.76	0.23
2	33	0.3685	293.50	0.13
3	31	1.1655	311.25	0.37
4	22	0.9619	291.92	0.33
5	19	0.8293	313.41	0.26
6	22	0.7874	258.07	0.31
7	43	0.6018	284.29	0.21
8	39	0.2850	272.36	0.10
Average	29	0.7120	291.57	0.24

Eight different random loading conditions were applied to the system and the GA program was run for each of the cases. Table 1 shows the minimum number of iterations required for each set of loads with the best fitness (I_N) reached as well as the normalised values I_N relative to the equal share of the per-phase load current for each of them. The last row of Table 1 shows the average of each column.

It can be easily spotted that the maximum percentage error (relative uncompensated neutral current) is less than 0.4% in all cases. This is quite acceptable for the case of an electrical power system phase balancing.

It is worthwhile to note here that the computation times of GA algorithm is generally large compared to other computation technique. The technique used in this paper took around 10.1 minutes in order to perform the computation. This in effect depends on a large number of factors such as the population size and the computation accuracy. This time is relatively large for fast varying application and renders the system impractical for such load cases. On the other hand, loads such as computer loads in commercial company buildings do not change that fast. The lighting and ventilation would amount to the same as well. Such computation times obtained in this paper would be rather suitable. Other techniques and measures would be considered in order to accelerate the computation process. This would be the subject of other research.

VII. Conclusion

A proposed control system for automatic transfer of electrical loads across phases in order to reach a minimum unbalance condition; i.e., minimum neutral current was presented in this paper. The accompanying optimisation algorithm using Genetic Algorithms was also presented. The problem formulation as well as the GA implementation is also presented. The system was proved to reach minimum unbalance of less than 0.4% for all the eight different loads of 100 nodes each. The maximum number of iterations reached was 39 generations, which is quite reasonable from the point of view of system hardware implementation.

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