MITIGATION OF SEVERE UNEQUAL SHARING OF THE LOAD CURRENTS IN MEDIUM-VOLTAGE SINGLE-CORE PARALLEL CABLE-FEEDERS

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ABSTRACT

Severe unequal sharing of load currents between the single-core cables of the parallel feeders in the medium voltage distribution network has both operational and economical deficiencies, which negatively impact the performance indices of the distribution companies. In this work, this phenomenon has been deeply studied. A methodology for an inexpensive solution to this problem is proposed. The results of implementation proved the capability of the proposed technique for the mitigation of the problem.

INTRODUCTION

Single core XLPE parallel cable feeders are used as incomers to the distributors in the Egyptian Medium Voltage (MV) Distribution System. Two parallel feeders are used to meet the growth of the demand, and to increase the continuity of power supply when one feeder fails. In some cases of such cable installations, severe unequal division of the load current, between the parallel cables of the same phase, has been observed. One of the cables is heavily loaded, while the other is lightly loaded.

Moreover, an apparent residual current having values that exceed the setting of the earth-fault protection of those parallel feeders causes their frequent tripping without any real fault in the system. In some cases, increasing the earth-fault protection setting to a higher acceptable value, although decreases the sensitivity of this protection, doesn't help. Some incoming feeders, when connected in parallel even without load, trip momentarily due to the operation of their earth-fault protection under the effect of such high residual current. If one of the two parallel feeders is disconnected, the load currents in the remaining connected feeder become balanced. The operators were obliged to disconnect one of the two parallel feeders and use it as standby, sacrificing the reliability of the power supply.

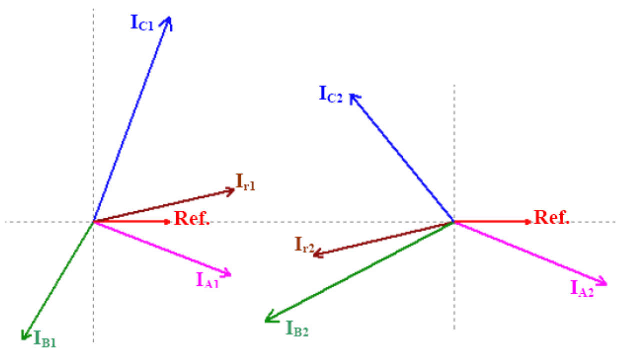
This phenomenon has, beside the above mentioned operational problems, some economical deficiencies. It limits the loading of the parallel cables to their maximum designed load value. The disconnection of one of the two parallel feeders, using it as standby, represents idle investment. The severe unequal current division may cause excessive heating of the heavy loaded cables which reduces its life time due to insulation degradation caused by the excessive temperature rise. The technical and economical performance indices of the distribution company become low due to the increased interruption rates of the power supply.

In order to obtain a uniform distribution of currents in parallel cables, a special device was introduced in [1]. The device is a ferromagnetic kernel which encloses the cable and carries a secondary coil loaded with adjustable burden. For two parallel feeders, this method requires addition of six such devices and performing fine tuning for their burdens after installation. The drawbacks of this method are its additional cost and the losses dissipated in the kernels and burdens.

In this paper we investigate and analyze the phenomenon and suggest a methodology for an inexpensive solution for the mitigation. The proposed solution is accomplished by rearranging the cable terminals' connections of the two feeders at both ends. The new arrangement is decided by a specially designed program which simulates the network of the case under study. The program is fed by the cable bundle parameters obtained by field measurements.

INVESTIGATION AND ANALYSIS

It is well known that a slight load current displacement in such single-core parallel cable feeders may occur due to slightly different induced voltages or slightly different impedances of the parallel paths as a result of the unavoidable different geometry of the cable arrangement. But, in the cases discussed in this paper, the differences between cables load current magnitudes and phase angles are drastic.



(a) Feeder F1 (b) Feeder F2

Fig.1 Phase and Residual Currents

For one of the cases, the measured phasor diagrams of the phase and residual currents in the two parallel feeders are shown in Fig.1. The values of the phase currents in Amperes are: I_{A1}=78, I_{B1}=73, I_{C1}=117 and I_{A2}=88, I_{B2}=113, I_{C2}=89. The residual currents have values of I_{r1}=I_{r2}=77 A. It can be seen that neither the three phase currents of each feeder nor the currents in the parallel cables are similar in magnitude, or have similar phase shifts. The magnitude of the current in one cable may reach multiple times the current magnitude in another cable. Also, the phase shifts may be extremely different from the known 120˚.

In fact, uniform division of the load currents between the MV parallel cables can only be achieved by bundling, transposition and symmetrical laying of the parallel cables in flat or trefoil arrangement. In practice, cable laying may face difficulties of limited space, where symmetrical geometry or transposition may be impossible. In large and crowded cities such as Cairo, it may be extremely costly and difficult, if not impossible, to find new roots with enough spaces. Under such conditions, the voltages induced in each of the two parallel cables of each phase may be greatly different in magnitude and/or phase. In some cases the resultant induced voltage in the three loops, formed by each two parallel cables as shown in Fig.2, may reach some tens of volts. This causes flow of circulating currents in the order of some tens of amperes in the loop.

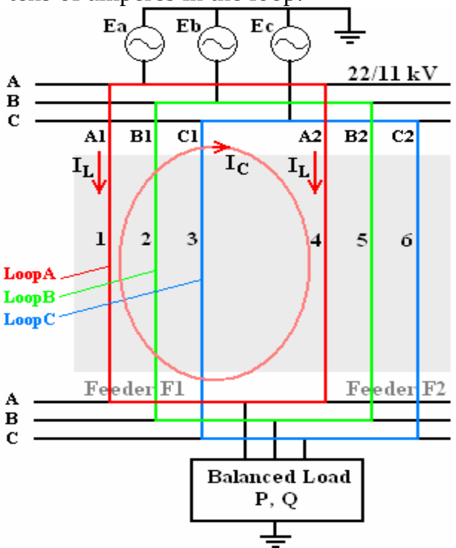
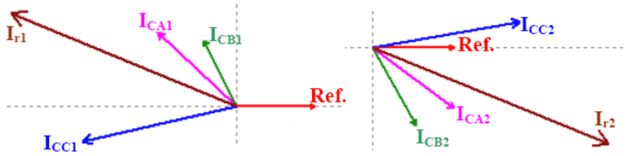


Fig.2 Network under Study

Fig.2 illustrates the network under consideration which includes:

- A source consisting of three phase voltages Ea, Eb and Ec.
- A balanced three phase load represented by its active power (P) and reactive power (Q).
- Two feeders: F1 including cables 1, 2 and 3; and F2 including cables 4, 5 and 6.

Each of the three phase currents of one feeder can be considered as consisting of two components: the current (I_L) which is equal to the half of the balanced load current, and the circulating current in the loop (I_C). For example, I_C in Loop A adds to the current I_L in cable 4 and subtracts from I_L of cable 1. This causes the severe unequal cable currents. Since the load currents are balanced, the sum of the three phase currents is then equal to the sum of the three circulating currents. Because circulating currents in the three phases are not balanced, as they depend on the unsymmetrical induced voltages, their sum will result in a residual current. The circulating and the residual currents in one of the parallel feeders will be equal in magnitude and opposite in phase with respect to their corresponding currents in the other feeder.



(a) Feeder F1 (b) Feeder F2

Fig.3 Circulating and Residual Current Phasors

Fig.3 shows, for two unloaded parallel feeders, the measured phasors of the circulating and residual currents, created by induction from some other neighboring loaded cables. Currents in feeders F1 and F2 are out of phase, which proves the above mentioned conclusion.

THE PROPOSED METHODOLGY

The studies of load current distribution between parallel conductors have been addressed for Low Voltage multi-conductor per phase arrangements [2-4]. The purpose of those researches was how to arrange cables and position them, in a new installation, to obtain balanced current distribution among the cables of each phase.

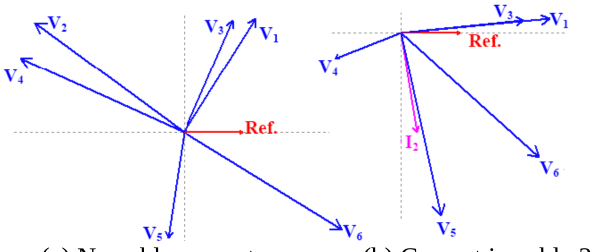
In this paper, the idea for mitigating the above mentioned problems, arising in old or new unsymmetrical cable installation, is based on leaving the cables under ground as they are, but rearrange the cable terminals' connections at both sides (source and load) in a way that reconfigures new three loops giving the minimum possible circulating and residual currents. The methodology proposed in this paper is based on field measurements and simulation work as explained below.

Although this methodology is illustrated for two parallel feeders' arrangement, it can be applied to any number of parallel feeders provided performing the suitable field measurements and simulation.

Field Measurements

In [2-4], the self and mutual impedances of the cables are calculated depending on a known configuration. Due to the difficulty of including the effect of the currents in the shield or sheath on the self and mutual impedances in the MV cable arrangement [5], this effect was approximated or ignored [6].

The real values of the self and mutual impedances of a highly unbalanced cable arrangement are greatly difficult to calculate, but field measurements of these impedances consider all factors such as the effect of the different geometry of the cable arrangement, effects of the shield and sheath currents…etc, and give real data of those impedances. The impedances for six cables of two feeders can be determined in the field as follows:



(a) No cable current (b) Current in cable 2

Fig.4 Induced Voltages

Fig.4a shows the measured induced voltages in the six cables (created by the neighboring loaded cables) without current flowing in any of the cables. Fig.4b shows the induced voltages in cables nos. 1, 3, 4, 5 and 6 when there is a current (I_2) flowing in cable no.2. The self impedance of cable no.2 and the mutual impedances between cable no.2 and the other five cables are calculated using the data represented in Fig.4. Such measurements have to be conducted six times for a current flowing in one of the six cables at a time. Using the measured data, the self and mutual impedances of the six cables can be obtained.

Simulation

The simulation of the network shown in Fig.2 (using the source, load and measured cables' parameters) is done by commercially available software, where such a network can be solved iteratively by numerical techniques. A special program, designed for solving the problem under study, runs for all possible permutations for reconfiguring the three loops by rearranging the six cable terminals in the six positions at both feeders' ends. For each permutation, the six cable currents $[I_{ph}]=[I_1, I_2 \ldots I_6]$, the circulating currents in the three loops I_{CA}, I_{CB} and I_{CC}, as well as the residual currents (I_{r1} and I_{r2}) are given in the program output. Three indices are used for evaluation of the different permutations; they are:

1- The value of the residual currents (I_{r1} and I_{r2}).
2- The value of the difference between the maximum and the minimum phase current (I_d), where I_d=max $[I_{ph}]$-min $[I_{ph}]$.
3- The loss index (L) which is the sum of the squares of the circulating currents in the three loops, $L= I_{CA}^2+I_{CB}^2+I_{CC}^2$.

The permutations which have the best (minimum values) of the above mentioned indices are selected as candidates for the solution. From those candidates, the permutation that requires minimum efforts in the field for implementation (rearranging the six cables' terminals at both ends) is selected as the best solution for mitigating the effects of the problem under study.

Verification

In order to check the coincidence of the program calculations, Table.1 holds a comparison between the phase and residual currents calculated by the program and the actual measured values of these currents in the original arrangement of the cables (1 2 3 4 5 6).

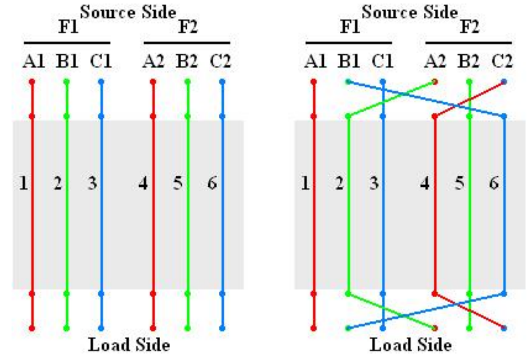
Table.1 Verification of the simulation results

		Measured Values		Simulation Values		Difference%	
		Amp	Deg	Amp.	Deg.	Current	Angle
F1	I1	109	-36	113	-35	3.7	-2.8
	I2	110	-152	112	-154	1.8	1.3
	I3	140	76	137	77	-2.1	1.3
	Ir1	30	42	30	40	0.0	-4.8
F2	I4	119	-27	118	-28	-0.8	3.7
	I5	120	-149	118	-148	-1.7	-0.7
	I6	98	103	102	104	4.1	1.0
	Ir2	31	-135	30	-140	-3.2	3.7

The comparison shows that the program results coincide with the measured values with a maximum difference less than ± 5%, which is practically acceptable. This result proves also that the self and mutual impedances' parameters, as measured and used in the program, reflect the real life.

Implementation

By application of the methodology and the program output, the best possible gains can be achieved without touching the cables underground. This can be done simply by rearranging the cable terminals' connections of the two feeders at both ends.



(a) Original arrangement (b) New arrangement

Fig.5 Cable Terminals Rearrangement

Fig.5 illustrates an example of how the new connection arrangement (163254) can be obtained instead of the original arrangement (123456). In both arrangements, the sequence of the cable numbering means their connection to the phases A1, B1, C1, A2, B2 and C2 respectively.

CASE STUDIES

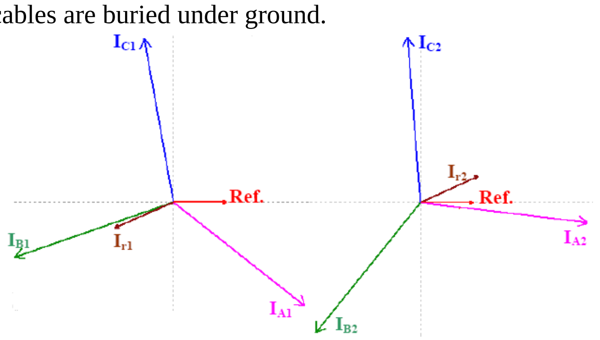
This methodology has been applied for several cases within the Egyptian Distribution System. Table.2 illustrates the results of implementation for three cases. The table shows the values of the indices used for evaluation of the results: namely I_r, I_d and L, before and after implementation. For comparison, measurements before and after the implementation are taken at approximately the same loading conditions.

Table.2 Results of case studies

Index		Case1	Case2	Case3
Ir (A)	Before After	77 28	92 51	168 3
	Improvement	64%	45%	98%
Id (A)	Before After	44 16	95 24	98 25
	Improvement	64%	75%	74%
L (A²)	Before After	1746 730	7618 5041	5862 1865
	Improvement	58%	34%	68%
New Cable Arrangement*		214356	523614	235416

* In all cases, original Cable Arrangement is 123456

Results illustrated in Table.2 shows that valuable improvements have been achieved by applying the methodology and implementing the program results. In case 3, complete elimination of the residual current has been reached. In fact, the degree of improvement is different from case to another depending how the existing cables are buried under ground.



(a) Feeder F1 (b) Feeder F2

Fig.6 Phase and Residual Current of Case 1

Fig.6 shows the phase and residual currents of case 1 after implementing the program recommendations. The values of the phase currents in Amperes are: I_{A1}=99, I_{B1}=95, I_{C1}=84 and I_{A2}=86, I_{B2}=83, I_{C2}=86. The residual current value is I_{r1}=I_{r2}=28A. By comparing Fig.6 with Fig.1 (which shows case1 before implementation), it is clear that the load currents became more balanced. In addition, the maximum current dropped to 99A instead of 117A.

CONCLUSIONS

The operational and economical impacts of severe unequal sharing of load currents between MV single-core parallel cable feeders have been discussed. Investigation of this problem revealed that, where bundling, transposition and symmetrical laying in flat or trefoil arrangement of cables is impossible due to the limitation of space, highly unbalanced induced voltages in the single-core parallel cable feeders is created and this causes circulating currents which result in great differences in phase currents beside and apparent residual current. A computer program is specially designed for mitigation of this problem. The cable impedances are determined by field measurements. The program output gives the best cable terminals' arrangement to have best current sharing and minimum residual current as well as minimum losses due to the circulating currents. Implementation of the program results for actual cases in the Egyptian Distribution Network has proved its effectiveness.

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