FUZZY LOGIC BASED OVERCURRENT PROTECTION FOR MV NETWORKS

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Abstract – In the paper a novel approach to overcurrent protection stabilisation based on Fuzzy Logic technique is presented. The scheme is intended for MV overhead lines for which the autoreclosure function is applied to enhance reliability of supply in case of intermediate (vanishing) faults. Protection stabilisation is required for the feeders supplying a part of network with numerous loaded MV/LV transformers that may face inrush conditions after reenergising the line. Traditional harmonic restraint approach as for single transformer may not be effective for line overcurrent protection because of different current spectrum as measured at the MV busbars. The new FL protection developed takes both current and voltage signals for further processing and final decision is issued as a result of aggregation of partial decision support coefficients. Application of signal fuzzification and fuzzy settings enables obtaining a relay with increased sensitivity, reliability and much faster than commonly available solutions. The developed fuzzy protection scheme has been tested with EMTP signals and compared with other standard protection approaches.

Keywords: overcurrent protection, fuzzy logic, transformer inrush, relay stabilisation

1 INTRODUCTION

Overcurrent (OC) principle belongs to the oldest and widely used criteria in power system protection. It is often applied as primary protection for distribution lines, small transformers and motors as well as a backup protection of transmission lines, transformers, generators and motors. The idea of the method is simple, however, it has also numerous drawbacks. Overcurrents are characteristic for phase and ground faults, but can also occur during normal operation, e.g. when energising power transformers, induction motors etc. The overcurrent criterion can thus be used for detecting faults, providing overcurrents of the kind mentioned above either cannot occur in the particular system or are prevented from causing tripping by functions included in the protection (e.g. time delay, blocking by harmonic detectors, discrimination by pick-up setting etc.).

Distribution networks in Poland are mainly of the radial structure. The overhead lines, cables and transformers in such MV networks are usually protected with use of time-overcurrent protection relays. In case of such OC protection short peaks of current, which are higher than the pick-up setting but shorter than the time delay (fixed or depending on the current level) cannot cause tripping of the circuit breaker. Since the majority of faults in MV networks are of transient (arcing) nature, i.e. they disappear either spontaneously or as a result of tripping the faulty feeder, the autoreclosure (ARC) relays usually supplement the main OC protection. Excluding persistent fault cases, the ARC schemes enable fast re-establishing of the normal state of the power system, thus restoring power supply to the customers. Reenergising the feeder after defined dead time may be successful after single shot or, sometimes, after two or more attempts. In case of MV feeders supplying a part of network with numerous MV/LV transformers certain problems with OC relay setting may be faced due to inrush phenomena in loaded transformers after successful ARC cycle. Restoring the power supply may result in temporarily increased currents measured at the relay location, which can be interpreted as overcurrent and consequently lead to feeder tripping (Fig. 1).

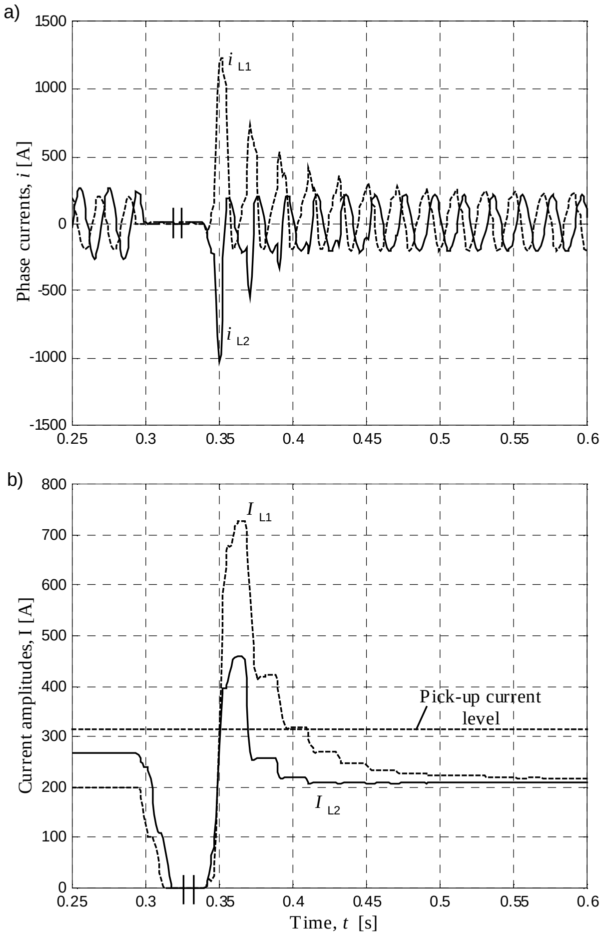

Figure 1: Phase currents for a successful ARC case: a) instantaneous signals, b) measured amplitudes.

In the paper the OC protection operation in distribution networks is studied, with particular consideration of mentioned above effects of ARC on line-transformer feeders. EMTP-ATP model of a fragment of typical Polish MV network as well as the simulation results of a few of ARC-cleared fault cases are described. Furthermore, a new algorithm of the OC relay stabilisation with application of Fuzzy Logic is described and its performance is compared to traditional stabilisation versions with harmonic blocking (second, or second, third and fifth harmonics). The FL reasoning unit developed takes advantage of parallel fuzzy processing of numerous criteria (current fundamental component amplitude, harmonic content, etc.) and their fuzzy aggregation, leading to final protection decision.

The proposed fuzzy OC protection scheme has been tested with the signals generated with use of EMTP-ATP programme as well as field recordings. The designed protection proved to be reliable and much more sensitive than the traditionally used OC relays, assuring sufficient stabilisation for the cases of transformer inrush currents evoked by autoreclosure operation.

In the next sections the structure and algorithms of Fuzzy Logic based relay is described (section 2). Its testing and comparison with chosen standard versions of OC protection is presented (section 3). Concluding remarks (section 4) close the paper.

2 FUZZY LOGIC BASED PROTECTION

2.1 Fuzzy Systems in power system protection

The fuzzy signal processing and fuzzy reasoning techniques (belonging to the family of Artificial Intelligence) have gained remarkable attention for at least 15 years and numerous studies have been performed in world-leading research centres with regard to their application also for power system protection and control tasks. Fuzzy Logic systems (FL) are well suited for solving various decision-making problems, especially when the precise analytical model of the process/object to be tracked is not known or is very complicated (e.g. non-linear) [2]. Analysis of power system faults and other abnormal phenomena belongs to the family of tasks that can be quite well carried out with use of FL-based decision modules or classifiers.

Fuzzy Inference Systems (FIS) employ the theory of fuzzy sets and fuzzy if-then rules to derive an output. Various types of FIS are often used either for fuzzy modelling or fuzzy classification purposes. Typically a FIS scheme performs its action in several steps including (Fig. 2):

- fuzzification (comparing the input values with membership functions to obtain membership values of each linguistic term),
- fuzzy reasoning (firing the rules and generating their fuzzy or crisp consequents),
- defuzzification (aggregating rule consequents to produce a crisp output).

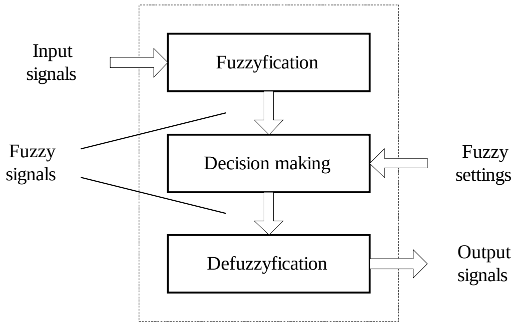

Figure 2: Basic structure of a fuzzy reasoning system.

The theory of fuzzy sets has met considerable approval for the sake of ability to describe quantitatively the uncertainties appearing during the operation of a protective relay. Implementation of fuzzy criteria signals together with fuzzy settings brings antidotes to uncertainties caused by dynamic measurement errors and may constitute a remedy against problems related with sharp boundaries in the universe of criteria signals between areas of faulty and failure-free operation of protected plant. Sample applications of this approach to power system protection include fault type identification [3] and multi-criteria protection of power transformers [4]. An idea of FL-based generator protection against out-of-step conditions was developed by the authors of this paper and published at the IEEE PES Summer Meeting in Vancouver in 2001 [5].

In the literature one can find also protection or control schemes employing a fuzzy processing module supplemented with other techniques, e.g. neural networks, wavelet transformation, etc. The resulting hybrid structures combine the strengths and eliminate weaknesses of particular techniques, which brings about increased efficiency and reliability of the scheme. Applications of fuzzy hybrid solutions are e.g. fuzzy-wavelet scheme for fault classification [6] and location [7] as well as fuzzy-neural distance protection [8].

2.2 Fuzzy Logic overcurrent protection developed

In this paper a fuzzy approach to overcurrent protection of MV feeders is studied. The protection solution developed (Fig. 3) takes advantage of fuzzy signal processing and fuzzy comparison to issue trip decision.

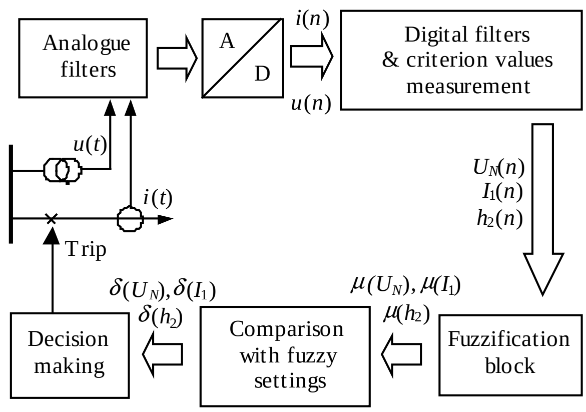

Figure 3: Block scheme of the FL-based OC protection.

The first three blocks in Fig. 3, i.e. analogue filters, A/D converters and digital signal processing unit, are typically applied in contemporary digital protection relays. At the output of this path certain criterion values are issued, basing on which the protection decision is to be worked out, usually by their comparison with pre-set thresholds or characteristics. Here, additional signal processing is performed to obtain fuzzified criterion

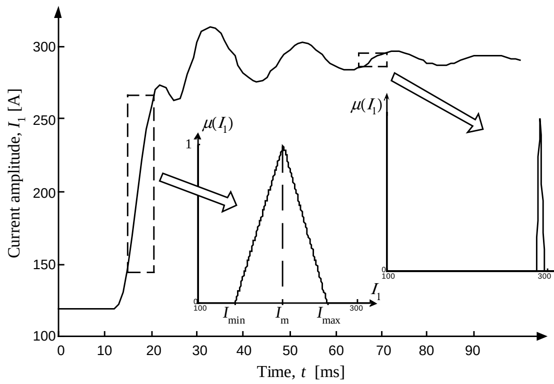

Figure 4: Sample current amplitude signal with respective fuzzy values (for two selected time intervals).

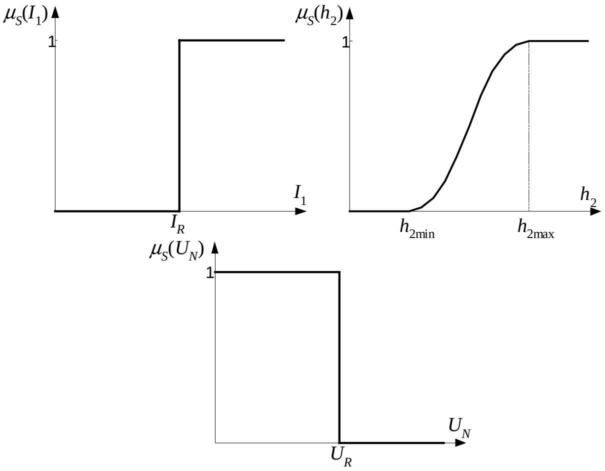

Figure 5: Membership functions of fuzzy settings of the signals I_1, U_N, h_2.

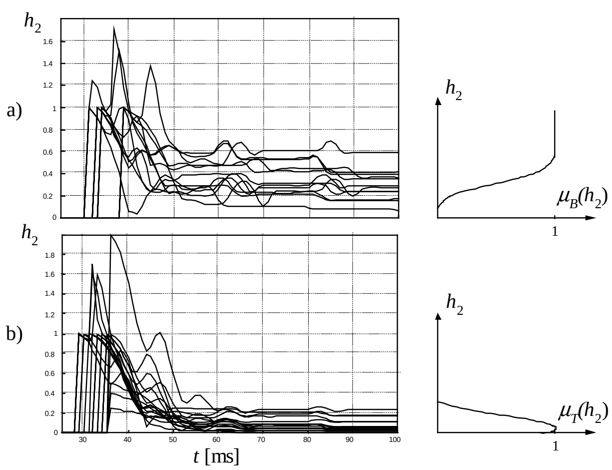

Figure 6: Illustration of membership function adjusting on basis of simulation data for the cases with: a) unsuccessful ARC, b) successful ARC.

signals (Fig. 4). Signal fuzzification is made according to the following formulae:

$$X_m(n) = \frac{1}{N_1/4+1} \sum_{k=0}^{N_1/4} X_1(n-k)\,, \tag{1}$$

$$X_{\max}(n) = \min_{k=0,\ldots,N_1/4} \{X_1(n-k)\}\,, \tag{2}$$

$$X_{\min}(n) = \min_{k=0,\ldots,N_1/4} \{X_1(n-k)\}\,. \tag{3}$$

which can be interpreted as finding minimum, maximum and average values of the criterion signal X over a time period corresponding to a quarter of fundamental frequency cycle, with N_1 being number of samples within 20 ms. The criterion signals taken into account were: amplitude of fundamental frequency phase current I_1, relative level of second to fundamental harmonic h_2 (a ratio of amplitudes I_2/I_1) and line-to-line voltage amplitude U_N. All the amplitudes were calculated with application of full cycle Fourier algorithm (sine-cosine filters plus determination of complex vector norm). The latter two variables are intended to serve as protection stabilisation criteria. High values of coefficient h_2 indicate temporary increase of second harmonic current I_2, which may take place either due to MV/LV transformers inrush phenomenon after successful ARC cycle or as an effect of current transformer saturation during switching the feeder on a persistent fault (unsuccessful ARC). To discriminate between the two cases the voltage amplitude is additionally measured, with decreased values indicating a persistent fault on the line.

The criterion signals mentioned are fuzzified in order to obtain a relative measure of their membership to given group of cases. The fuzzy criterion signals are compared with fuzzy settings that have been set as shown in Fig. 5. The fuzzy setting μ_S for current amplitude I_1 and voltage amplitude U_N are crisp (sudden change from 0 to 1 or from 1 to 0 after exceeding certain threshold value), while the function $\mu_S(h_2)$ is a kind of saturable curve, changing gradually from 0 to 1. Its shape and parameters have been found after analysis of the level of I_2 for numerous cases of faults with successful and unsuccessful ARC (Fig. 6). The result of fuzzy comparison (see Fig. 7, here for variable h_2) is defined as a ratio of the area F under both setting and signal membership functions and the area F_1 under criterion signal membership function:

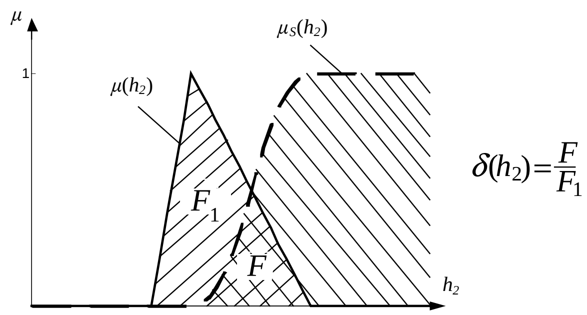

Figure 7: Comparison of fuzzy signal with fuzzy setting.

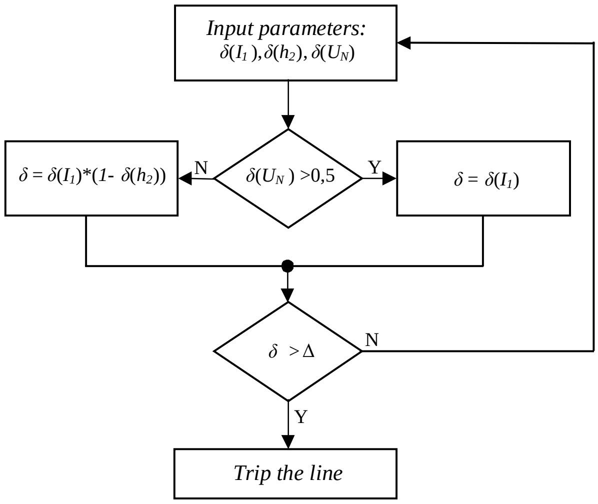

Figure 8: Block scheme of the decision making.

$$\delta(X) = \frac{\int \min[\mu(X), \mu_S(X)]dX}{\int \mu(X)\, dX} = \frac{F}{F_1}. \qquad (4)$$

As a result of fuzzy comparison the non-fuzzy coefficients $\delta(I_1)$, $\delta(U_N)$, $\delta(h_2)$ are determined. The calculated values of δ specify the degree of satisfying of given criterion (degree of confidence of exceeding the fuzzy threshold) and may amount between 0 and 1. The calculated variables are interpreted as follows:

1^0 if $\delta(I_1) = 1$ & $\delta(h_2) = 0$ – a clear indication on a persistent fault is issued, which implies necessity of immediate line tripping;

2^0 if $\delta(I_1) = 1$ & $\delta(h_2) = 1$ & $\delta(U_N) = 0$ – a situation of magnetising inrush in MV/LV transformers in the depth of network (supplied from the feeder to be protected) is confirmed, i.e. the feeder should not be tripped;

3^0 if $\delta(I_1) = 1$ & $\delta(h_2) = 1$ & $\delta(U_N) = 1$ – the second harmonic current I_2 is evoked due to saturation of current transformers, which, simultaneously with full support for exceeding of fundamental frequency current threshold I_1, gives a reliable indication on line-to-line fault, i.e. the feeder should be tripped.

The situations listed above encompass only the most extreme and unquestionable cases. The space in-between the cases 1^0 to 3^0 includes, of course, all uncertain situations which are also expected to be well handled by the scheme. Thanks to introduced fuzzy features the borders between the classes of events to be discriminated become fuzzy and the decision, even for doubtful cases, may be taken with higher confidence. The block scheme of reasoning with fuzzy variables is shown in Fig. 8. Depending on the value of voltage related support coefficient $\delta(U_N)$, the final decision is met on the basis of either

- single-handed current support coefficient $\delta(I_1)$ – for $\delta(U_N)$ greater than 0.5, or
- a combined fundamental/second harmonic current support coefficient $\delta(I_1)(1-\delta(h_2))$ – for $\delta(U_N) < 0.5$.

High values of the resulting support coefficient δ are observed for the cases of persistent line-to-line faults with or without current transformer saturation, which indubitably should lead to line tripping. Other cases, including magnetising inrush situations, would imply relay stabilisation and further uninterrupted supplying of electrical energy to customers in the network.

3 RELAY TESTING AND COMPARATIVE ANALYSIS

3.1 MV network structure and testing signals

The new fuzzy logic based protection has been verified with use of signals generated with EMTP-ATP software. To obtain data for scheme testing a model of typical Polish radial MV network has been prepared (Fig. 9). The network under study (voltage level 20 kV) was operated with neutral point grounded via Petersen coil, i.e. with compensation of capacitive currents, connected through Zy grounding transformer. The feeders outgoing from MV busbars were of mixed type, i.e. overhead lines, cable sections or both. The MV lines were distributing power to numerous domestic and industrial loads connected to the network through dedicated 20/0.4 kV transformers, rated power from 63 kVA to 1.2 MVA. Some of the feeders were supplying power to 30 or even more MV/LV transformers. The ATP model of power transformer applied included details related to parameters of transformer windings, active and reactive power losses as well as non-linear magnetising characteristics with full hysteresis loop (ATP inductor model type 96). The simulation results obtained from the model prepared were of good conformity with the signals registered in a real MV network of similar structure [10]. It was also confirmed that the network model was sufficiently good for accurate rendering of phenomena related to faults and autoreclosure induced transients.

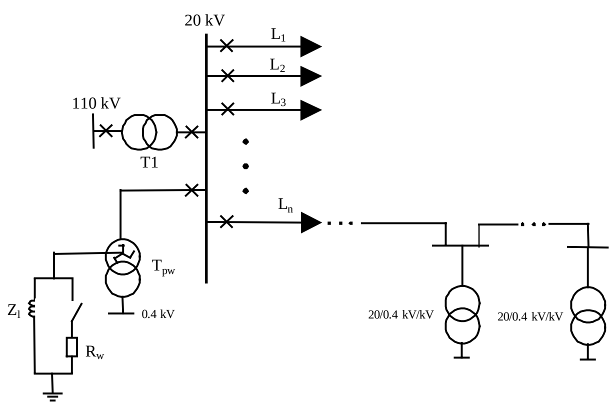

Figure 9: Structure of the MV network under study.

Various line-to-ground and line-to-line fault cases were simulated at the beginning and at the end of selected feeders in the network. The faults were of both transient and persistent type, with three-phase autoreclosure initiated for overhead lines. The protection has been tested with current signals from the cases with both successful and unsuccessful ARC. Such model parameters as feeder switching on angle (after ARC pause), degree of MV/LV transformer loadings, load type, etc. were being changed to obtain a wide variety of fault conditions. Feeder currents as well as MV bus-bar voltages were registered in ATP output files for further processing.

3.2 FL protection testing

The algorithms and logic of proposed fuzzy overcurrent protection have been implemented in MATLAB programming code. Numerous testing attempts have been performed with the aim to optimise the relay fuzzy settings, threshold values and fuzzification window lengths. The optimisation goal was to obtain a protection solution characterised by possibly shortest operating time for persistent faults, yet being absolutely stable for transformer inrush cases after successful ARC cycle, at the same time.

Operation of proposed fuzzy overcurrent protection for MV lines has been compared with other versions of available OC relays:

A – classical OC scheme without stabilisation,

B – as A, supplemented with second harmonic restraint (set low or high) [9],

C – OC scheme with 2nd, 3rd and 5th harmonic stabilisation, as described in [11].

The scheme *B*, with second harmonic restraint, was modelled on simple stabilisation idea typically applied e.g. in transformer protection. A flag for exceeding certain amount of 2nd harmonic content was used for relay blocking purpose. The problems with proper setting of such a restraint will be shown below, which confirm impossibility of ideal solving of the sensitivity vs. stability dilemma with single crisp relay setting.

The solution *C* is based on correcting of OC relay input current by subtracting a current term related to transient components evoked by switching on the line after ARC pause, according to:

$$I_s(n) = k_s \frac{I(n-k)-I(n)}{I_N}\left(k_{2h}h2+k_{3h}h3+k_{5h}h5\right) \quad (5)$$

where: k_s – stabilisation coefficient, $I(n)$, $I(n\text{–k})$ – current samples before correction, I_N – nominal current of the protected overhead line, k_{2h}, k_{3h}, k_{5h} – coefficients of stabilisation for the 2nd, 3rd and 5th harmonic, respectively, $h2$, $h3$, $h5$ – percentage content of 2nd, 3rd and 5th harmonic currents. The corrected current value was further compared with typically set OC threshold.

Below two cases of ARC attempts for single-phase intermediate fault (relay blocking required, Fig. 10) and line-to-line persistent fault (fast tripping necessary, Fig. 11) are shown. Operation of overcurrent protection solutions *A* and *B* is compared with the new FL based relay developed. Direct comparison with version *C* was not possible here due to lack of all required parameters and relay settings.

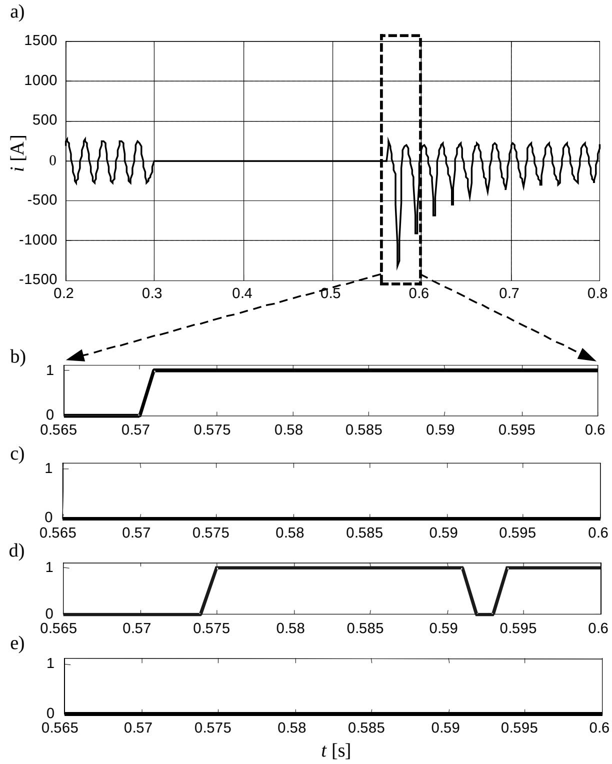

Figure 10: Operation of MV line protection for a case with successful ARC: a) phase current from the healthy phase, b) trip signal of the classic OC protection, c) trip signal of the OC protection with 2nd harmonic stabilisation – set low, d) as above – set high, e) trip signal of the FL based relay.

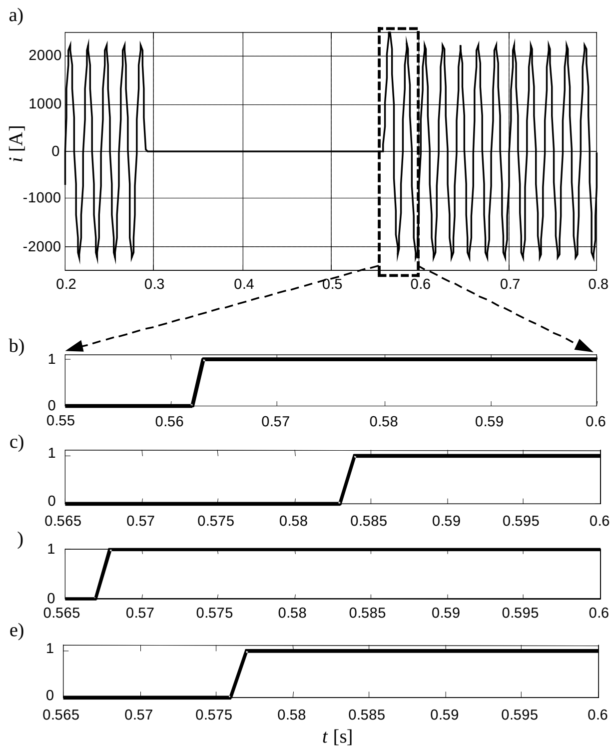

Figure 11: Operation of MV line protection for a case with unsuccessful ARC (line-to-line persistent fault): a) phase current observed, b) trip signal of the classic OC protection, c) trip signal of the OC protection with 2nd harmonic stabilisation – set low, d) as above – set high, e) trip signal of the FL based relay.

It is seen (Fig. 10b) that the classical OC scheme without stabilisation – version *A* – responded falsely to situation of healthy line switching on (overfunction). Numerous simulation runs have shown, as anticipated, that avoiding unselective trippings for magnetising inrush conditions after successful ARC is possible at a cost of increased trip delay (not less than 100 ms for most cases) or significant raising of relay pick-up setting (decreased sensitivity).

Application of relay blocking in dependence on the second harmonic level (OC version *B*) enables considerable increase of resulting relay selectivity (Fig. 10c). Nevertheless, choosing the restraint threshold should be made with care, since too small values may imply elongated operation time for persistent line-to-line faults (Fig. 11c), without complete elimination of possible unselective trippings for transformer inrush cases. It is obvious that along with increase of the 2^{nd} harmonic threshold faster relay operation is expected for persistent faults (Fig. 11d), yet by considerable deterioration of relay selectivity (Fig. 10d).

Comparison of the FL based scheme with the stabilisation algorithm with temporary current correction (version *C*) was performed indirectly, i.e. by using the result statistics given in paper [11]. The tests have shown that stable and selective operation of the relay *C* was obtainable with ca. 30 ms internal time delay. It should be stated, however, that such operation parameters could be reached with introduction of numerous coefficients and threshold values, which may unfavourably influence universalness of the scheme and cause problems by relay setting. The new FL-based scheme turned out to be even faster than relay *C*, being able to respond to all cases with time delay less than 20 ms. Such a high operation speed was obtained despite of the fact that for calculation of criterion values (amplitudes of I_1, I_2 and U_N) an algorithm with full cycle filtering was used. The relay *C* was a bit slower, although it employed much faster wavelet transformation for signal processing.

4 CONCLUSIONS

In the paper a new Fuzzy Logic based overcurrent protection for MV overhead lines is proposed. The scheme designed is well suited for interaction with standard autoreclosure relays. Its main feature is the improved stabilisation for transients evoked by switching on the feeder after successful ARC cycle due to possible inrush currents of supplied MV/LV transformers.

The FL-based OC protection scheme has been thoroughly tested with ATP-generated power system signals. The new relay was able to classify properly all the considered simulated fault/ARC cases. No unselective answers for transients due to transformer inrush have been observed. With FL algorithm the decisions were taken earlier and much more reliable than with use of other OC protection systems. Wide robustness features of the scheme with respect to changes of both network configuration and fault parameters have also been confirmed.

REFERENCES

[1] H. Ungrad, W. Winkler and A. Wiszniewski, *Protection Techniques in Electrical Energy Systems*, Marcel Dekker, Inc., New York, 1995

[2] J. M. Mendel, „*Fuzzy Logic Systems for Engineering: A Tutorial*", Proc. of the IEEE, vol. 83,No. 3, pp. 345-377, 1995

[3] A. Ferrero, S. Sangiovanni, E. Zappitelli, "*A fuzzy-set approach to fault type identification in digital relaying*", IEEE Trans. On Power Delivery, vol. 13, no. 4,pp. 169-175, 1995

[4] M.-S. Shin, C.-W. Park, J.-H. Kim, "*Fuzzy Logic-Based Relaying for Large Power Transformer Protection*", IEEE Trans. On Power Delivery, vol. 18, no. 3, pp. 718-724, 2003

[5] W. Rebizant and K. Feser, "*Fuzzy logic application to out-of-step protection of generators*", Proceedings of the 2001 IEEE PES Summer Meeting, 15-19 July 2001, Vancouver, Canada, paper 01SM061

[6] A. K. Pradhan, A. Routray, S. Pati, D. K. Pradhan, "*Wavelet Fuzzy Combined Approach for Fault Classification of a Series-Compensated Transmission Line*", IEEE Tran. On Power Delivery, vol. 19, No. 4, pp. 1612-1618, 2004

[7] J. Moshtagh, R. K. Aggarwal, "*A new approach to fault location in a single core underground cable system using combined fuzzy & wavelet analysis*", Eighth IEE International Conference on Developments in Power System Protection 5-8 April 2004,vol. 1, pp. 228-231

[8] P. K. Dash, A. K. Pradhan, G. Panda, "*A Novel Fuzzy Neural Network Based Distance Relaying Scheme*", IEEE Trans. On Power Delivery, vol. 15, no. 3, pp.902-907, 2000

[9] MiCOM P139 Manual, Alstom, Paris, France, 1999

[10]M. Michalik and A. Juszczyk, "*Modelling of Transient Autoreclosure Effects in Medium Voltage Networks for Overcurrent Relaying Purposes – Comparison of ATP Simulation and Field Measurement Relays*", Proceedings of European EMTP-ATP User Group Meeting, Wroclaw, Poland, September 2000, pp. 83-89

[11]A. Juszczyk and J. Lorenc, "*Stabilization of Transients in Overcurrent Protection during Fast Autoreclosure Operations in MV Networks*", Proceedings of the Modern Electric Power System Conference, MEPS'02, Wroclaw, Poland, September 2002, pp. 353-356