AN IMPROVED METHOD FOR HIGH IMPEDANCE FAULT DETECTION IN MIDDLE VOLTAGE NETWORKS

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Categorization of paper (Style: Ariel Narrow, 8pt)

This paper presents set of rules for an intelligent algorithm of high impedance fault detection by observing the phase to ground voltage, phase to phase current and harmonics of fault current. Several techniques to detect high impedance faults already exist: current injection in the neutral, superposing voltage signals, harmonic analysis, neural networks… The main disadvantage of all methods is that the normal system activity may cause false tripping of the protection device. Our goal is to give set of rules for an algorithm that can make a secure decision that a particular feeder event is high impedance fault. Set of rules was carried out from simulation results simulated in MATLAB. The proposed approach was trained and tested with 200 data sets and provides excellent results.

Keywords: fault detection, Fourier transform, high impedance fault, middle voltage network

UNAPRIJEĐENA METODA DETEKCIJE VISOKOOMSKIH KVAROVA U MREŽAMA SREDNJEG NAPONA

Kategorizacija članka (Style: Ariel Narrow, 8pt)

Ovim člankom predstavljen je skup pravila za inteligentni algoritam detekcije visokoomskih kvarova promatranjem faznih napona i struja, kao i harmonika struje kvara. Nekoliko metoda detekcije visokoomskih kvarova već postoji kao što su: injektiranje struje, superpozicija signala napona, harmonička analiza, neutronske mreže… Glavni nedostatak svih postojećih metoda detekcije visokoomskih kvarova leži u tome da zaštitni uređaji prepoznaju normalne sklopne operacije u mreži kao visokoosmski kvar (neželjena prorada zaštitnih uređaja). Cilj istraživanja bio je postaviti skup pravila za inteligentni algoritam koji može donijeti sigurnu odluku da li je do kvara došlo ili ne. Navedeni skup pravila je dobiven na temelju rezultata simulacijskog modela razvijenog u programskom paketu MATLAB. Navedeni pristup je ispitan s 200 skupova ulaznih podataka te daje odlične rezultate.

Ključne riječi: detekcija kvara, Fourierova transformacija, mreža srednjeg napona, visokoomski kva

1   Introduction

High impedance single-phase to earth faults (HIFs) in middle voltage networks are difficult to detect using conventional overcurrent, ground fault relays and some versions of distance relaying schemes [1]. This kind of fault is hard to detect by monitoring equipment because their presence result with only slight increase in phase to ground current and phase to ground voltage, thus can be confused with normal increases in load [2]. HIF is defined as unwanted electrical contact between an energized conductor and a high impedance surface such as asphalt road, sand, grass or tree [3]. This fault has a small current ranging from a few mA to tens of amperes [4]. The failure of HIFs detection leads to serious threat in electric shock to human beings and potential fire hazards [5].

HIF is a very complex phenomenon and exhibits very highly nonlinear behaviour [6]. High impedance faults are inherently nonlinear and always result in distorted current, so harmonic analysis is critical in the evaluation and determination of HIFs [2]-[7].

The detection of high impedance faults is certainly difficult [8]. In fact, as it was recognized in the conclusions of the Working Group D15 of the IEEE Power Engineering Society [9], "no matter what method is used, not all high impedance faults (HIF) are detectable" and "practically, it is impossible to detect all HIFs and at the same time achieve a high degree of security against false outputs." In the same sense, CIGRE Study Committee B5 reported that "all utilities have had and regularly continue to have undetected HIF records" and concluded that HIF detection is an important technical challenge that requires further research and efforts in order to achieve more reliable and effective solutions [10].

There are different ways of detecting and handling high impedance earth faults: direct measurement of the electric quantities of the power system, energy and randomness algorithms, harmonic analysis, neural networks, wavelet analysis and chaotic pattern analysis [11]. The features of the high impedance faults are extracted and invested using fuzzy logic, genetic algorithm and Kalman filtering, as well [11].

A detection technique is reliable and secure when it is capable of perfectly identifying and distinguishing the high impedance faults from other transients in network [12]. The problem is that normal switching events (such as feeder switching, capacitor banks switching) generate similar components as high impedance faults which results in false tripping of the protection devices [11]. Certain relay manufactures commercialized protection devices with HIF detection functions, but utilities that have tested them agree that the performance is not satisfactory [10].

In order to see the influence HIF has on the network, a simulation model using MATLAB Simulink was made. Our goal was to observe phase to ground voltage, phase to ground current, phase to phase voltage, phase to phase current and zero sequence current of the line in case of high impedance fault and in case of normal system activities. First, third, fifth and seventh harmonic of the zero sequence current was observed with the same target. A total of 200 simulations for various line lengths, fault resistances, the moment when a fault occurs were observed. 200 simulations gave 2600 data that were used to establish set of rules and to train the algorithm for high impedance fault detection. The proposed approach was trained and tested with 200 data sets and provides excellent results.

This paper presents a new approach for HIF detection using Fourier transform and design of intelligence system. The aim of this paper is to give an algorithm which discriminates high impedance faults against regular switching and switching of shunt capacitors.

## 2   Matlab Simulink simulation model

In order to describe the behaviour of the network during high impedance faults and during normal system activity simulation model was made using MATLAB SimPowerSystem software. SimPowerSystems provides component libraries and analysis tools for modelling and simulating electrical power systems [13]. With the intention to control results given by simulation models the mathematical model was created as well. The comparison of the simulation model results and calculated values show match [6]. A simulation model consists of: three-phase 110 kV source, network transformer 110/20 kV, middle voltage cables and overhead lines, series lead and element that represents a high impedance fault/normal system activity [14]. In this simulation model network transformer is earthed through arc suppression coil.

The different simulation conditions taken into consideration were:
- Three phase load switching (on and off);
- Three phase line without load switching (on and off);
- Three phase capacitor banks switching (on and off);
- Direct single line fault to earth ($R_f = 0$ Ω);
- High impedance fault ($R_f = 4000$ Ω, 15000 Ω, 50000 Ω);
- Various power line lengths (1 km, 20 km and 40 km);
- Various moments when a fault occurs ($t = 5$ms, 10 ms).
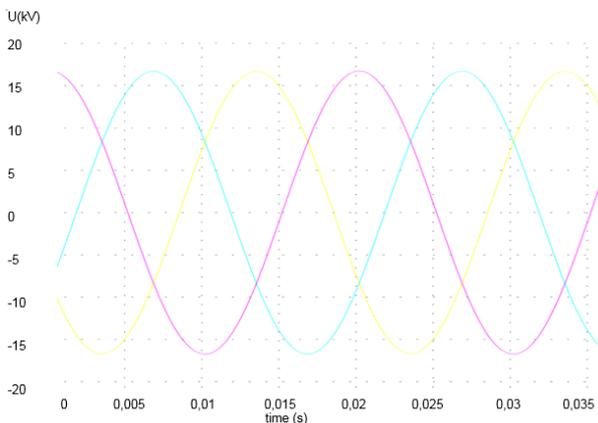
Figure 1 Phase to ground current of faulted line in case of high impedance fault
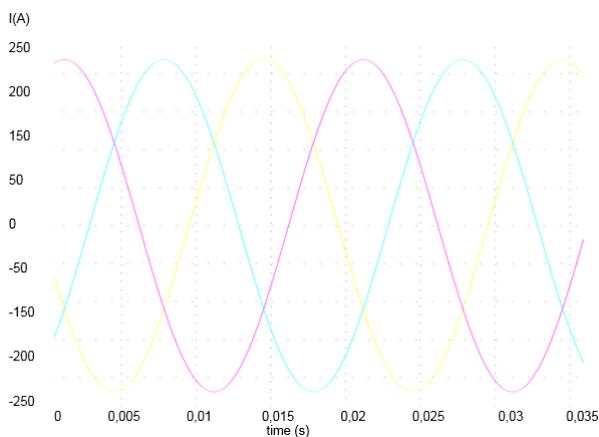
Figure 2 Phase to ground voltage of faulted line in case of high impedance fault

This model shows phase to ground currents and voltages as well as zero sequence harmonics of the observed line during fault/switching events and results can help in the decision whether the high impedance fault occurred or not. The idea is to develop an intelligent system that can process multiple algorithms and multiple parameters for secure high impedance fault detection. Figure 1 shows the behaviour of phase to ground current in case of HIF and figure 2 behaviour of phase to ground voltage. It is evident that HIF can't be detected just by observing specified values. The harmonics amplitude and angle give superior results for detection of HIFs than the fundamental component. The amplitude and phase of the first, third, fifth and seventh harmonic of the zero sequence line current were extracted using Fourier transform in order to decide whether fault occurred [15]-[16]. The goal is to combine all the results in intelligent algorithm which can be implemented in commercial electric power analysis software and commercial protection devices.

A set of indicators will be given to distinguish fault situations from other situations. The results obtained from simulation model will be foundation for algorithm which can improve the limitations of the present protection technology.

The main goal is to detect HIFs, discriminate them from normal system activities and to improve the reliability and security of the electric grid.

2.1 High impedance fault model

HIFs on electrical power distribution system involve arcing and nonlinear characteristics of fault impedance which cause a stochastic nonlinear current. The Emanuel arc model was presented in 1990. It is based on theoretical components and laboratory measurements [12]. Figure 3 shows Emanuel arc model. In this model, the arc in HIF is modeled using two DC sources, connected as anti-paralleled by two diodes. Many researchers have been using this model and tried to complete it. In 2014, a new model for high impedance fault in electrical distribution system was presented [12]. It uses several Emanuel arc models in parallel that combined produce HIF current similar to real recorded HIF current. Figure 4 shows improved HIF model. In order to see the behaviour of the network in case of high impedance fault and to get as many different situations both models were taken into account.

Figure 5 shows simulated zero sequence line current results in case of the classic Emanuel arc model. Figure 6 shows simulated results of zero sequence line current in case of the improved Emanuel arc model.
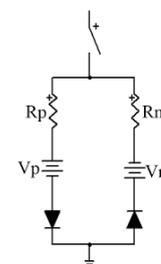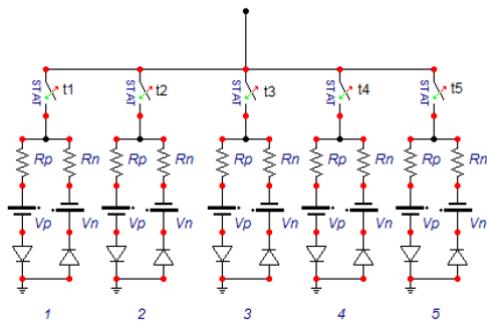

Figure 3 Emanuel arc model
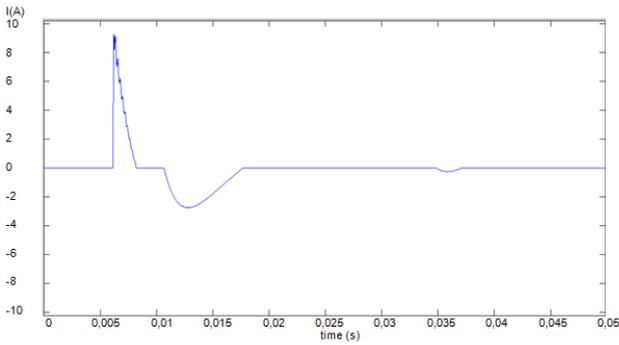
Figure 4 Improved Emanuel arc model

Figure 5 Zero sequence current in case of HIF (classic Emanuel arc model)
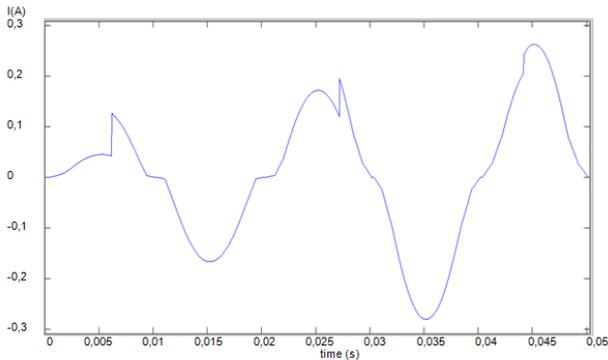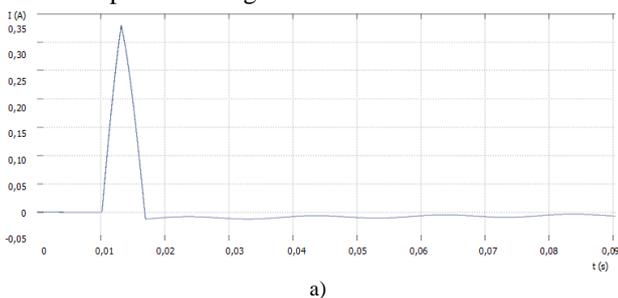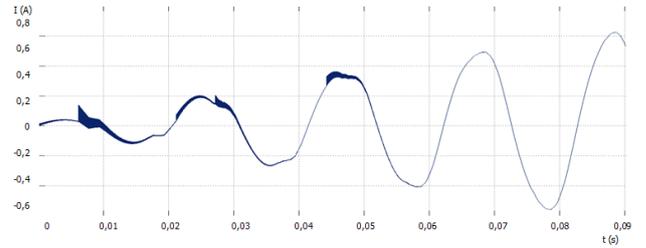

Figure 6 Zero sequence current in case of HIF (improved Emanuel arc model)

3   Simulation result

Results from 200 simulated events in Matlab were compared in order to make set of rules for the high impedance detection algorithm. Following figures will show simulation results in case of three phase line without load switching and in case of high impedance fault. The main goal is to show that just by observing amplitude of the zero sequence current and their harmonics it is not possible for the protection device to decide whether the fault occurred. That is the reason why phase to phase voltages and currents need to be incorporated in algorithm as well.
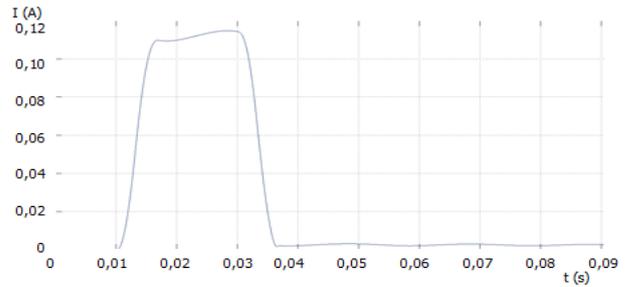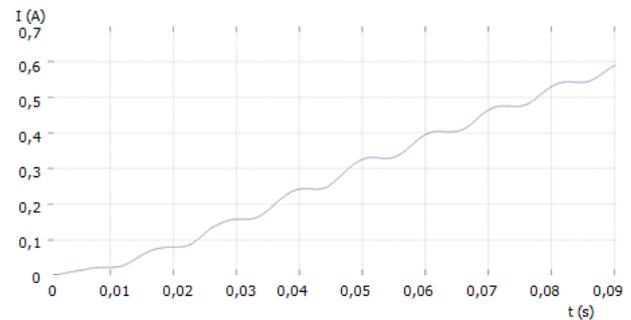

a)

b)
Figure 7 Zero sequence current in case of:
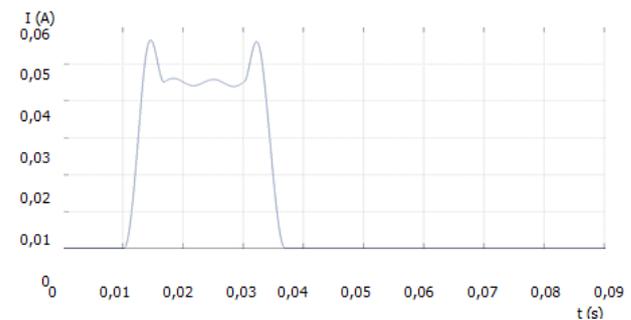a) Three phase line without load switching, b) HIF (improved Emanuel arc model).

a)

b)
Figure 8 First harmonic of zero sequence current in case of:
a) Three phase line without load switching, b) HIF (improved Emanuel arc model).

a)

b)
Figure 9 Third harmonic of zero sequence current in case of:
a) Three phase line without load switching, b) HIF (improved Emanuel arc model).
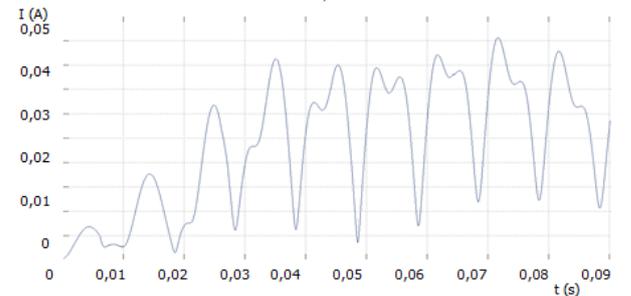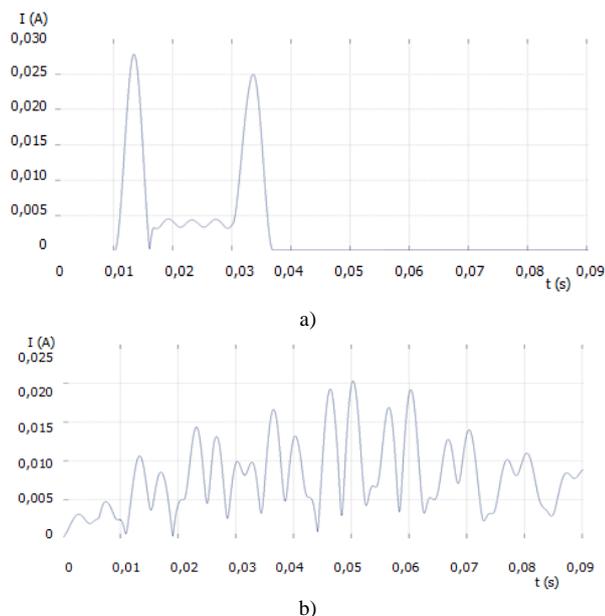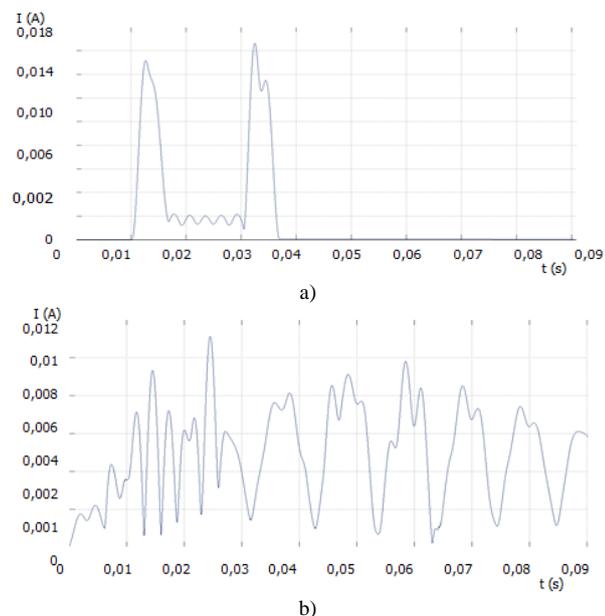
Figure 10 Fifth harmonic of zero sequence current in case of:
a) Three phase line without load switching, b) HIF (improved Emanuel arc model).

Figure 11 Seventh harmonic of zero sequence current in case of:
a) Three phase line without load switching, b) HIF (improved Emanuel arc model).

4   Discussion

After analysing all the results from 200 simulated events in MATLAB, set of rules for an algorithm of HIF detection and differentiation from normal switching condition was established [17]-[18]. U_{phtogr} is phase to ground voltage, I_{phtogr} is phase to ground current, $3 \cdot I_0$ refers to zero sequence line current, harmonics refer to first, third, fifth and seventh harmonic of the zero sequence current. Factor k relates to the ratio of phase to ground voltage after and before the simulated event occurs in the network (overvoltages). The proposed algorithm should include three important parts: input data, features generation and network activity (fault/not fault). In order to combine proposed algorithm in

electrical power system, zero sequence current relay with harmonic component needs to be installed. Phase to ground current and voltage, as well as zero sequence current of the line (amplitude and phase of first, third, fifth and seventh harmonic) should be measured and compared before (t_1) and after network event (t_2). Data obtained from the simulation model gave us rules for HIF detection. The goal is to achieve set of rules for protection devices that can be used in power system. The set of rules for determination weather the high impedance fault occurred or not is given in following lines.

Three phase load switching (on)
$k > 1$
$U_{phtogr}(t_2) > U_{phtogr}(t_1)$
$I_{phtogr}(t_2) > I_{phtogr}(t_1)$
Harmonics ≈ 0
$3 \cdot I_0 \approx 0$

Three phase load switching (off)
$k < 1$ OR $k \geq 1$
$U_{phtogr}(t_2) < U_{phtogr}(t_1)$
$I_{phtogr}(t_2) < I_{phtogr}(t_1)$
Harmonics $\neq 0$
$3 \cdot I_0 \neq 0$

Three phase line without load switching (on)
$k > 1$
$U_{phtogr}(t_2) > U_{phtogr}(t_1)$
$I_{phtogr}(t_2) > I_{phtogr}(t_1)$
Harmonics ≈ 0
$3 \cdot I_0 \approx 0$

Three phase line without load switching (off)
$k < 1$ OR $k \geq 1$
$U_{phtogr}(t_2) < U_{phtogr}(t_1)$
$I_{phtogr}(t_2) < I_{phtogr}(t_1)$
Harmonics $\neq 0$
$3 \cdot I_0 \neq 0$

Three phase shunt capacitors switching (on)
$k > 1.4$
$U_{phtogr}(t_2) > U_{phtogr}(t_1)$
$I_{phtogr}(t_2) > I_{phtogr}(t_1)$
Harmonics ≈ 0
$3 \cdot I_0 \approx 0$

Three phase shunt capacitors switching (off)
$1 \leq$ $k < 1.01$
$U_{phtogr}(t_2) \geq U_{phtogr}(t_1)$
$I_{phtogr}(t_2) = I_{phtogr}(t_1)$
Harmonics ≈ 0
$3 \cdot I_0 \approx 0$

Direct single line fault to earth
$k > 1.72$
$U_{phtogr}(t_2) > U_{phtogr}(t_1)$
$I_{phtogr}(t_2) > I_{phtogr}(t_1)$
Harmonics $\neq 0$
$3 \cdot I_0 > 200$ A

High impedance fault to earth
$k > 1$
$U_{phtogr}(t_2) > U_{phtogr}(t_1)$
$I_{phtogr}(t_2) = I_{phtogr}(t_1)$
Harmonics > 0
$3 \cdot I_0 \neq 0$

A novel technique for detecting high impedance faults and discrimination HIFs against regular network switching showed very satisfying results. After testing 200 various conditions that can occur in distributive networks advantages

of algorithm were confirmed. In the event of a high impedance fault the feeder's response becomes different from the normal operations. The normal network operations taken into consideration were three phase load switching (on and off); three phase line without load switching (on and off) and three phase capacitor banks switching (on and off).

5   Conclusion

High impedance fault detection is a significant problem for protection engineers. This paper gives the reasons that led to the development of new algorithm for high impedance fault detection and discriminations against regular network switching. The proposed set of rules allows algorithm to recognize if HIF has occurred. The set of rules for algorithm were obtained from hundreds of simulation results. It is expected that HIF detection in future will be even more important due to higher demands for reliability of power supplied to customers. Future work should further investigate the combination of the proposed set of rules for algorithm with existing algorithms for high impedance fault location. The algorithm can be combined with existing commercial electrical power system analysis software to discriminate clearly between fault and non-fault events.

Acknowledgements

Appendix

Parameters of simulation model are given here:
Network frequency: 50 Hz;
Source: Three-phase 110 kV ideal source;
Network transformer: 110/21/10.5; 40 MVA; YNynD5;
Load power: 20 MVA;
Load power factor: 0.95;
Middle voltage (20 kV) cables and overhead lines length variation: 1km, 20 km and 40 km

Table 1 Specifications of middle voltage power line

Power line type	Resistance per unit length (Ω/km)	Inductance per unit length (H/km)	Capacitance per unit length (F/km)
Cable	$R_d = 0.206$	$L_d = 0.39\cdot10^{-3}$	$C_d = 0.251\cdot10^{-6}$
	$R_0 = 0.7749$	$L_0 = 1.702\cdot10^{-3}$	$C_0 = 0.439\cdot10^{-6}$

Classic Emanuel model parameters:

$R_n = 9000\ \Omega$, $R_p = 12000\ \Omega$, $V_n = 4000$ V, $V_p = 4500$ V

Improved Emanuel model parameters:

Table 2 Improved Emanuel model parameters

Parameter	Arc 1	Arc 2	Arc 3	Arc 4	Arc 5
t (ms)	6,2	21,1	44,2	44,2	27,2
R_n (kΩ)	90	129	135	135	140
R_p (kΩ)	120	130	130	130	140,1
V_n (V)	4000	8000	7500	7500	490
V_p (V)	4500	8100	7600	7600	510

XX   References

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