Line Differential Protection with Synchrophasor Data in WAMPAC System in Control Room

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***Abstract*—Wide area monitoring system (WAMS) installed in Croatian Transmission system operator (HOPS) control center collects and process synchrophasor data in real time. There are ongoing activities on continuous, incremental and gradual upgrading of existing WAMS with new protection functions and control algorithms towards WAMPAC system. This paper describes line differential protection based on synchrophasor data and implemented on PDC server running in control room. In the first phase, the algorithm was applied to historical synchrophasor data. That check revealed that estimation block in PMUs at both line ends must implement the same estimation technique. Because of this finding, only lines with the same PMU type on both ends were selected for real-time performance test in the second phase. Several months long performance test successfully confirmed a soundness of concept and its implementation. It was proven in practice that new algorithm can be used as an effective tool for validation of basic protection performance and a solid foundation for development and implementation of backup protection.**

Keywords—line differential protection, synchronized measurement data, WAMS, PMU, line backup protection

I. Introduction

Communication infrastructure and IT technology in contemporary Transmission System Operator's (TSO) control rooms [1] enables gathering of numerous types of data which can then be used in wide array of applications and with different functions. Wide Area Monitoring System (WAMS) being one of them, collecting synchronized measurements from high voltage transmission lines. Currently it is being upgraded and additional protection [2] [3] and control functionalities are being implemented to create Wide Area Monitoring, Protection And Control (WAMPAC) system [4]. Protection function uses the same data already gathered by WAMS and is used for line differential protection for transmission lines. This newly established protection functions are still working without tripping high voltage circuit breakers in switchyard.

WAMPAC data are processed in a way that makes possible for protection functions to work in real time and enables complete surveillance of faults on protected line. Furthermore it gives insights of classical relay protection system operation in control room [5] [6]. That also opens possibilities to design some central protection functions. Data flow is transferred to WAMPAC system from each of Phasor Measurement Unit (PMU) 12 channels, with three phase and positive, negative and zero sequence of voltage and current.

Line differential protection is implemented on 400, 220 and 110 kV transmission lines. This protection's algorithm based on synchronized measurement data is comparable with relay protection device functions.

Line differential algorithm ΔI> or 87L in WAMPAC system is made according to IEC 60617 and ANSI/IEEE C37.2 standards. Module within WAMPAC consists of the following:

- Module for calculating vector differences between current and voltage synchrophasors on transmission line ends in real time and storing that data in historical data base.
- Module for triggering protection actions according to designed set parameters for line differential protection.
- Interactive interface for visualizing current and historical data within schematic display of transmission system.
- Interface for setting parameters of line differential protection.
- Interface with alarm list.

Module for calculating difference between current phasors in real time has been implemented on all of lines equipped with PMUs capable of calculating difference on only positive sequence, and whereas on lines equipped with newer generation PMUs difference between negative and zero sequence can also be calculated.

PMU device of newer generation that are capable of generating negative and zero sequence enabled a new approach to equipment monitoring and measuring of both normal and disturbance condition on lines.

II. Hardware platform for protection functions in control room

Endeavour to form WAMPAC system in Croatian TSO (HOPS) resulted in defining a device to perform as a source of synchrophasor measurement data for WAMPAC system. Four fundamental requirements had to be met for this new extended PMU:

- Package of all synchrophasor values and status data which is transferred through 2 supervisory systems Phasor Data Concentrator (PDC) with 20ms resolution has to contain synchrophasors of all phases and symmetric components of current and voltage.

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- Device has to be made according to minimal dimension for rack installation (1U standard) in order to fit into existing cabinets without additional reconfiguration of already installed control and protection devices.
- Device has to be able to connect to metering and protection cores of current transformers.
- Device has to enable reverse action of WAMPAC system on field elements (circuit breaker) in switchyards.

Based on this requirements PMU device of newer generation with extended set of phasor values which are generated and sent towards WAMPAC system in accordance to IEEE norm [7] was developed. Communication capabilities are also expanded so the device has two communication channels, primary and secondary [8].

The primary channel is faster and of higher priority and enables TCP/IP and UDP/IP connectivity via a 100 MB/s Ethernet link. It allows four concurrent connections on which according to IEEE C37.118.2 protocols synchrophasor packages are sent to the master PDC systems. In this particular installation, two flows of packages with synchrophasors of all phase values and all symmetric components of voltages and currents and statuses of binary inputs and outputs are sent, at a time resolution of 20 ms, via the process network to the control room and two identical PDC applications running on the primary and secondary PDC server. The third synchrophasor stream is delivered to the test PDC server (Wamster). On this server, which is also deployed in the NDC, a validation of the line differential protection application solution presented in this paper is implemented. The fourth primary channel connection is free to accept additional communication.

A secondary communication channel of lower priority, speed and reliability is established using a built-in modem for mobile network communication. This channel connects SterPMU-R1 to the Wamster web application. The principle of operation of both communication channels is shown in Figure 1.

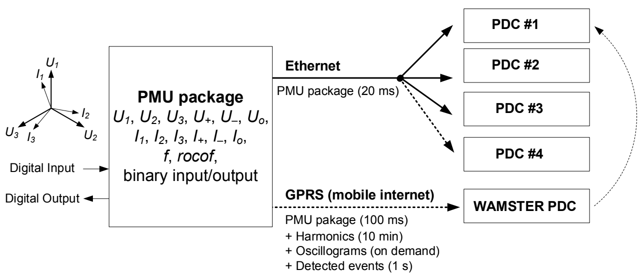

Fig. 1. Block scheme for communications channels from new PMU device

The new synchrophasor unit fulfills the requirements of HOPS in terms of migration of the existing WAM system to the WAMPAC system. The properties of the advanced synchronization PMU, without which it is not possible to achieve new functionalities at the level of control centers have been tested in a months-long trial. Under normal operation conditions and disturbance conditions, the correct operation and accuracy of measurements in every situation the transmission network can be found are confirmed. Significant enhancement of the communication functionality of the device enables the sending of all phase quantities and all three-phase voltage and current components in 20 ms resolution to the three parent WAMPAC systems, while simultaneously monitoring the parameters of the operating device via the lower priority service link and the web interface are possible.

Testing module for transmission line differential protection was successfully added to the third PDC server and an analysis of transmission line events was performed on HOPS historical data. At the events it was determined that the protective relay operated within 3 synchrophasor packets, that is, it took a maximum of 60 ms from the detection of the jump in the amplitude of the current phasor difference vector and the relay trip.

It has been found that in power lines where different models of PMU devices (new STER PMU-R1 and 15 years old PMU) are installed at the ends is not possible to reliably detect internal faults, due to vector differences between synchrophasors responding to step changes [9].

III. LINE DIFFERENTIAL PROTECTION FUNCTION

A. Algorithm for line differential protection

The transmission line protection algorithm is based on the calculation of the differential current, that is, the vector sum of synchronized current phasors at the ends of the transmission line. According to Kirchhoff's law (1), the vector sum of all currents in a closed circuit is equal to zero:

$$\sum_{k=1}^{N} \vec{I}_k(t) = 0 \qquad (1)$$

The simplest configuration of instrument transformers is to place current transformers at both ends of the transmission line, at all three phases, where the current directions are set so that the positive orientation of the current vector at both ends is toward the transmission line (2). Then the vectors are ideally opposite in phase and equal:

$$\vec{I}_{Af} + \vec{I}_{Bf} = 0 \qquad (2)$$

where $\vec{I}_{Af}$ vector of current at phase f at one end and $\vec{I}_{Bf}$ vector of current at phase f at the other end of the transmission line.

In practice, the vector sum of the current phasors will have an amplitude different than zero caused by the loss of current to the line resistance, while in the case of power line failures, there will be a large deviation before the protection is operated. Line differential protection is based on the differential current of the transmission line (3):

$$\vec{I}_{df} = \vec{I}_{Af} + \vec{I}_{Bf} \neq 0 \qquad (3)$$

where $\vec{I}_{df}$ is the differential current of one phase of the transmission line. The line differential protection algorithm (4) uses the amplitude of the real component of current vector I_{Df}:

$$I_{Df} = \left|\vec{I}_{df}\right| = \left|\vec{I}_{Af} + \vec{I}_{Bf}\right| \qquad (4)$$

When the transmission line is energized from one end, the charging current I_{cf} of the transmission line is

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permanently present, which dominates the differential current of the transmission line (5), so:

$$\vec{I}_{Af} + \vec{I}_{Bf} + \vec{I}_{cf} = 0 \tag{5}$$

For the purpose of the algorithm, a simplification was introduced that neglects the voltage drop on the transmission line, meaning it is considered that the voltage on the transmission line is constant. Then a voltage from one of the ends of the transmission line can be used in the expression for the charging current of the transmission line. In the server algorithm, for leading voltage a side of the transmission line is selected, where in the normal mode the positive direction of the active power is measured, and the specified voltage can be used to obtain the impedance of the line (6):

$$\vec{I}_{df} = -\vec{I}_{cf} = -\frac{\vec{U}_f}{\vec{Z}_f} \tag{6}$$

where $\vec{U}_f$ is the phase voltage at one end of the transmission line, $\vec{I}_{cf}$ is the phase charging current of capacitive character, and $\vec{Z}_f$ is the impedance of the line with the majority of capacitive character (7):

$$\vec{Z}_f \approx jX_c \tag{7}$$

where X_c is capacitive reactance, that is $X_c < 0$.

The amplitude of the differential current caused by the capacitive component is 5 - 15% of the amplitude of the rated current of the transmission line, that is, if there is no fault on the transmission line, then it is valid that (8):

$$I_{Do} \approx 0.15 \cdot I_n \tag{8}$$

where I_n is rated transmission line current and I_{Do} amplitude of differential vector in normal operation.

With continuous charging current, large false differential currents can occur at higher loads or external faults, caused by transient saturation of current transformers. In order to reliably detect transmission line faults, the threshold for triggering an alarm is therefore defined by a curve that is a function of the sum of the amplitudes of the currents at the ends of the transmission line.

Given that such loads can cause differences in the measurements at the ends of the transmission lines, it is necessary to calculate the restrain current I_{Rf}, defined as the sum of the amplitudes at the ends of the transmission lines, (9):

$$I_{Rf} = |\vec{I}_{Af}| + |\vec{I}_{Bf}| \tag{9}$$

It is then possible to define the conditions for the tripping of the line differential protection depending on the magnitude of the differential current amplitude I_{Df}, the magnitude of the restrain current I_{Rf}, and their mutual ratio.

B. Line differential protection characteristic

The load curve of the transmission line load is typically divided into three sections according to Figure 2. The first section of the protective device tuning curve is defined by the minimum limiting value of current that is canceling the influence of the charging current, I_{Dmin}, and the ultimate limiting current of the first section I_{Rs1}.

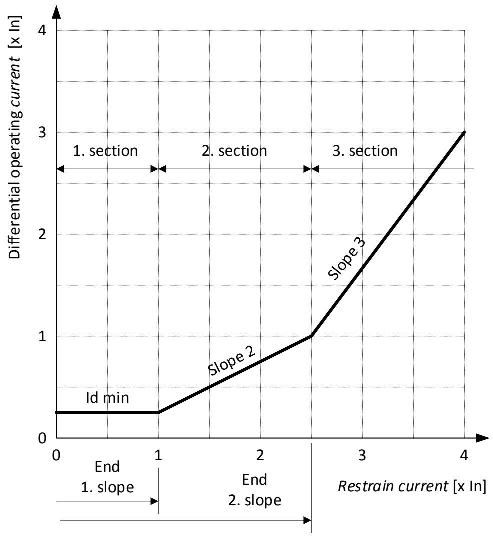

Fig. 2. Operating characteristic for line differential protection

The usual value of I_{Dmin} is 30% of the rated current, which suppresses the sum of the two amplitudes of the previously mentioned transmission line charging current of max. 15%, according to expression (8).

In the second section of the curve, a linear dependence on the magnitude of the limiting current (10), $slope_{s2}$ is being added to the limiting current I_{Dmin}.

$$slope_{s2} = \frac{\Delta I_{Df}}{\Delta I_{Rf}} \cdot 100\% \tag{10}$$

The third section has a slightly higher slope in practice, as shown in Figure 2. The condition for triggering the protection in WAMPAC module is in Table I.

TABLE I. LINE DIFFERENTIAL PROTECTION CONDITION FOR TRIPING

$I_D(t) > I_{Dmin}$	for $I_R < I_{endS1}$
$I_D(t) > I_{Dmin} + (I_R(t) - I_{endS1}) \cdot slope_{S2}$	for $I_{endS1} \leq I_R < I_{endS2}$
$I_D(t) > I_{Dmin} + (I_{endS2} - I_{endS1}) \cdot slope_{S2} + (I_R(t) - I_{endS2}) \cdot slope_{S3}$	for $I_{endS2} \leq I_R$

The following table describes the range of parameters for the WAMPAC line differential protection module, Table II.

TABLE II. RANGE OF PARAMETAR FOR LINE DIFFERENTIAL MODULE

Parameter	Range	Unit	Initial Value	Description
Id min (I_{Dmin})	0.20 – 2.00	x In	0.30	Basic sensitivity of section 1 as nominal current fraction (initial value 30%)
End S1 (I_{endS1})	1.00 – 2.00	x In	1.00	End of section 1, as a fraction of the rated current
End S2 (I_{endS2})	1.00 – 10.00	x In	3.00	End of section 2, as a fraction of the rated current
Slope S2	10.0 – 100.0	%	50	Slope of section 2, ratio of operating and

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($slope_{S2}$)				limiting current
Slope S3 ($slope_{S3}$)	30.0 – 100.0	%	100	Slope of section 3, ratio of operating and limiting current

Fault detection using the line differential protection algorithm was implemented with the highest priority in the Wamster-RT server process, to reduce the impact of the operating system on the total detection delay.

After receiving the data packet for a specific time badge from both PMUs, Wamster-RT calculates the differential and restrain current, and in case of fault detection can sends a priority message via the C37.118 command frame to the defined PMU devices.

IV. Line differential protection operation on faults in transmission network

Line differential protection module was implemented in WAMPAC system in control room and during the test phase operations, this module was compared with common relay protection operation on real fault in transmission network. Also, numerous analyses [10] were made to check many parameters in this new module.

Two characteristic faults in transmission network and response of line differential protection module will be analyzed.

- Faults on line or inner faults is important to present the response of this new module.
- Stability of protection algorithm can be checked on outside faults. One case of busbar fault will be elaborated.

A. *Example of fault on 220 kV transmission line*

There was a two-phase fault of the Brinje-Konjsko transmission line (phases L1 and L3) on 3 May 2019 at the time 14: 26: 05: 580. The fault currents at both ends of the transmission lines were several kA, as seen in Figure 3 and Figure 4.

The fault was properly switched off after 60 ms, by switching off the circuit breakers at both ends of the transmission lines at 14: 26: 05: 640. The transmission line is switched on after 5 minutes at 14:30:24.

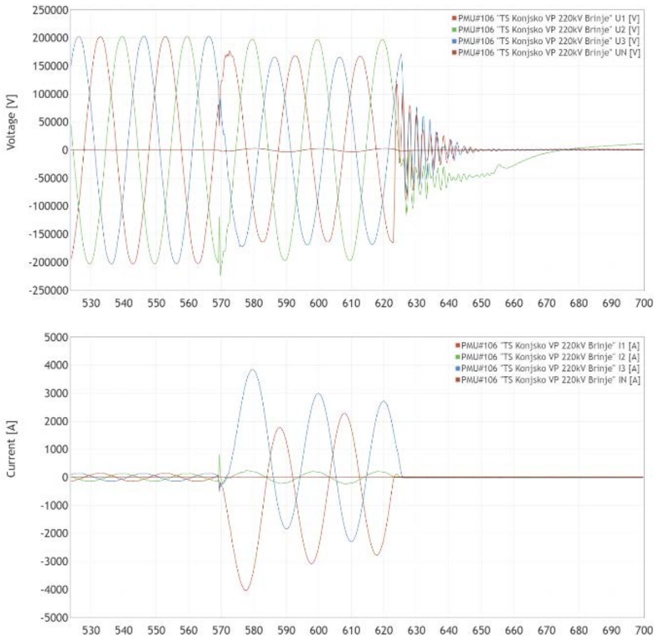

Fig. 3. All three phase voltages and currents during the two phase line fault in substation Konjsko, line 220 kV Brinje

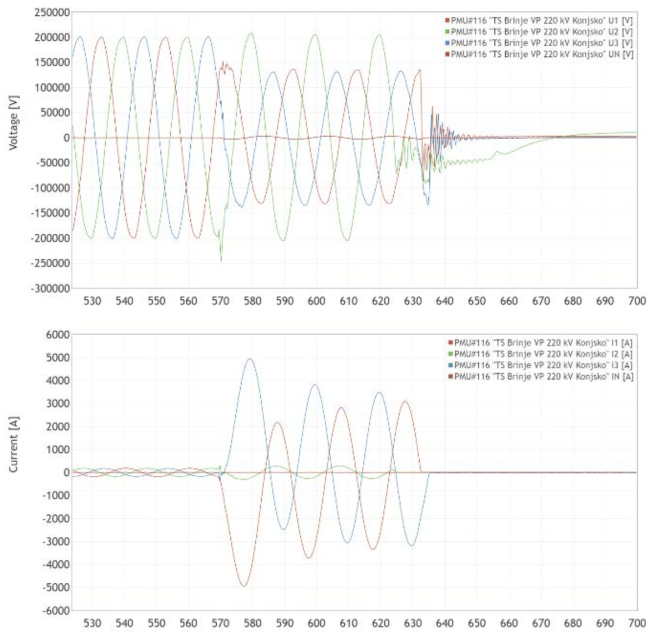

Fig. 4. All three phase voltages and currents during the two phase fault in substation Brinje, line 220 kV Konjsko

Through the service link, the waveforms of phase voltages and currents shown in Figure 3 and Figure 4, were collected. The waveforms present a very clear picture of the events on the transmission line for all three phases and are very similar to the waveforms generated by the relay protection devices and can serve for quality fault analysis.

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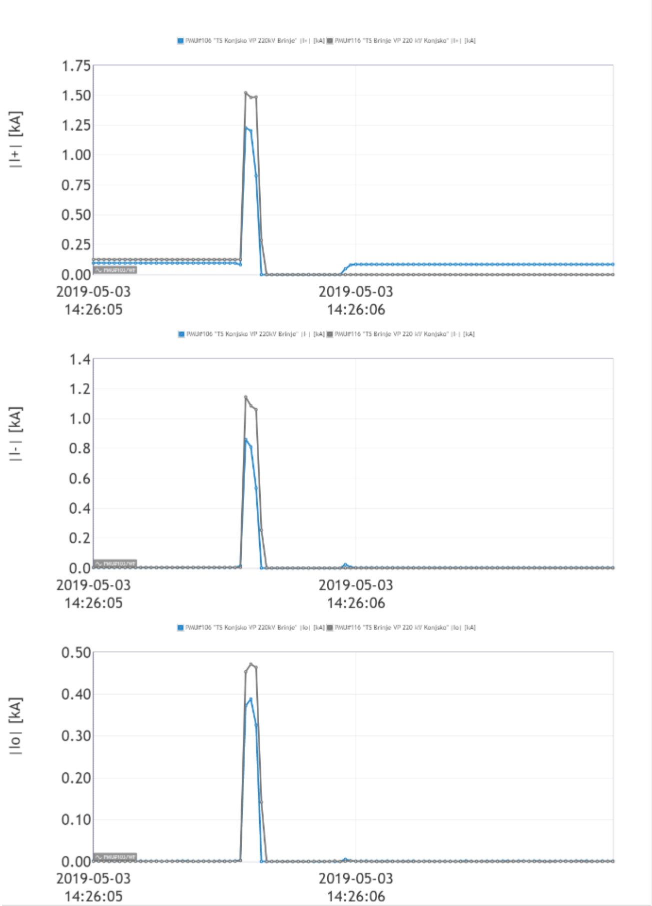

Fig. 5. Amplitude for positive, negative and zero current component for both line ends on line Brinje-Konjsko

Positive, negative and zero current component for this faults, were calculated in new algorithm, Figure 5.

For the fault recorded, Figure 3 and Figure 4, the line differential protection algorithm in the WAMPAC module measured a differential fault current (positive component) of 2.8 kA, Figure 6. The values of differential positive, negative and zero current components are shown on Figure 6.

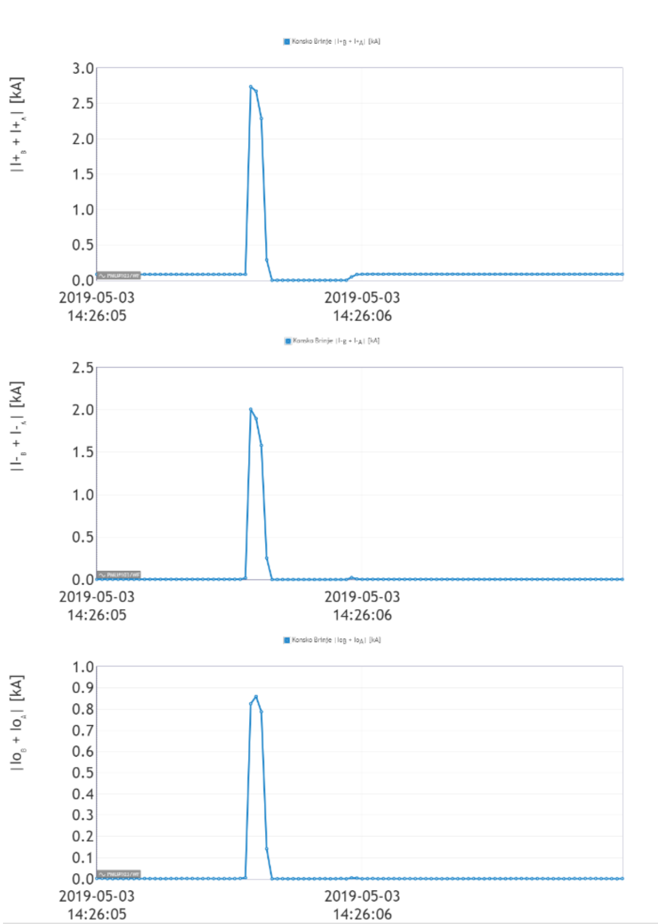

Fig. 6. Vector sum for positive, negative and zero current component for both line ends on line Brinje-Konjsko

The new generation of devices are connected to the protection current cores of the measuring transformer, as is the relay protection device itself. In this way, fault currents can also be monitored, which was not the case with earlier generations of PMUs.

The algorithm in the WAMPAC system makes available to relay protection engineers very similar data as relay protection devices themselves. The ability to export data is easier and can be obtained in the usual .csv formats. The data is stored on the PDC server continuously and saved from 6 up to 36 months, so in the case of more complex failures or frequent failures, there is much less chance that the data will not be recorded and stored for later analysis [10].

B. Example of fault on 400 kV busbar

Correct operation of the line differential protection function is also important for external faults, for which this protection must remain stable and operated to a close external short circuit or activate in cases of large faults current. In this particular example of a bus failure, the line differential protection algorithm worked as expected. The fault occurred in the 400 kV network at the buses in substation Velebit on 28.05.2019. at 19.31. hours. Transmission line 400 kV Velebit-Konjsko has a new generation of PMUs installed on both sides, which neatly generated synchrophasor data that was transmitted to the WAMPAC system. The fault current on that line was over 4 kA, measured by both PMUs at both ends, Figure 7 and Figure 8. The phase voltages and currents for the fault in question are showed, which is switched off in the second

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stage of the distance protection on that transmission line, and the total fault is eliminated a little later.

Fig. 7. All three phase voltages and currents recorded in substation Velebit for line 400 kV Konjsko, during busbar faults in substation Velebit

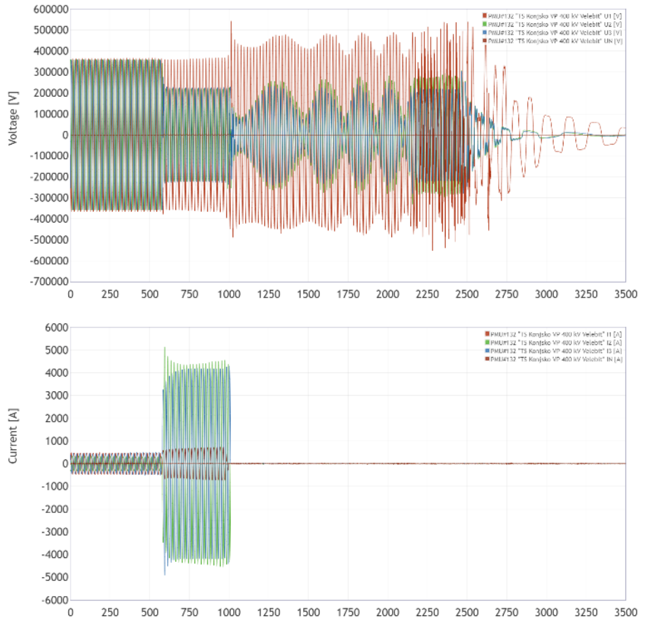

Fig. 8. All three phase voltages and currents recorded in substation Konjsko for line 400 kV Velebit, during busbar faults in substation Velebit

The fault dataset collected in the WAMPAC system shows the full potential for real time operation and further use for analysis purposes. Also, these PMU devices are connected to the protection cores of the metering (instrument) transformers.

Differential and restrain currents for this busbar faults are shown in Figure 9. The figure shows the values for 4 transmission lines near the fault location, on which there is an activated line differential protection algorithm in WAMPAC system. For the 400 kV Velebit-Konjsko and 110 kV Velebit-Obrovac transmission lines, there are higher differential and stabilization currents. Whereas for the remaining two transmission lines that are electrically further away from the fault location, these amounts are much smaller.

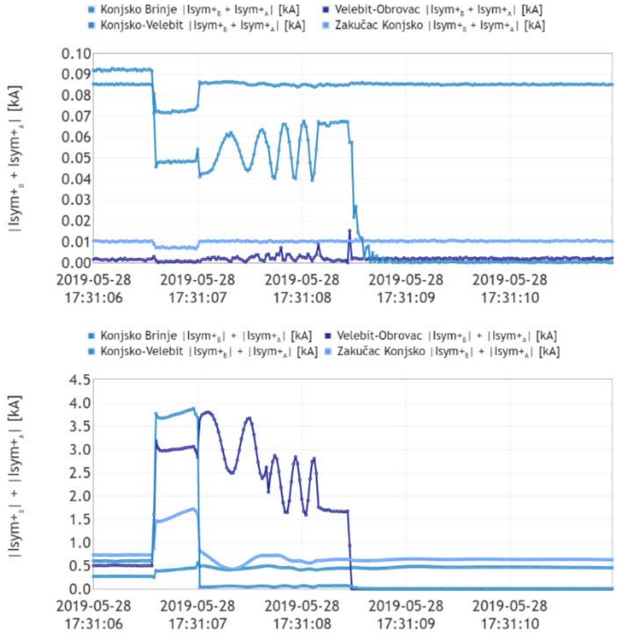

Fig. 9. Differential and restrain current for four transmission lines in vicinity of busbar fault on 400 kV

This example shows the suitability of the operation of the line differential protection algorithm for transmission lines located near the fault location. For farther transmission lines, the algorithm worked properly and registered a fault.

V. Conclusion

The real-time monitoring system of the wider transmission network provides an opportunity for direct, continuous and timely insight into the system status at the monitored points. The timeliness of available data can be used to upgrade the existing WAMS monitoring system with new security features and control algorithms in the gradual transition to the WAMPAC system.

As data is continually collected and stored on PDC data servers, it is possible to design new algorithmic concepts first and then validate them based on a set of real, historical data stored in the synchronous measurement databases.

This paper presents the basic aspects of development and practical results of application of line differential protection of transmission lines. The solution was implemented and tested on a Wamster PDC server in control room, which through process communication collects and processes synchrophasor data from STERPMU-R1 devices. After the initial coding of the computational algorithm and the pages for the user interface, the validity of the developed algorithm was checked by processing one-year data stored in the database of synchronous measurements. The validation confirmed the expectation that different principles of the estimation of synchrophasors would give different results for highly variable input signals. Therefore, it is necessary to use PMU devices that have been implemented according to the same recommended synchrophasor calculation procedures in protective functions operating within a few tens of milliseconds. For this reason, the line differential protection

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algorithm of transmission lines is activated in real time only on transmission lines that have paired types of PMUs.

Real-time testing of the application solution for several months confirmed the validity of the set concept and the correct implementation of security algorithms. A sophistically developed user interface that provides easy access to current and historical data, as well as an overview of the WAMPAC differential protection alarm list is an effective tool for monitoring the correct operation of basic transmission line protection in off-line mode. The automatic storage of syncrophasor measurements paired with voltage waveforms and fault currents collected through the service channel provides additional insight into the nature of the failure for analysis and is available up to three years after its occurrence.

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