Using Phasor Measurement Unit in Control Room for Monitoring Frequency Primary Regulation of Generator Unit

Igor Ivanković
Croatian Transmission Operator, HOPS
Zagreb, Croatia
igor.ivankovic@hops.hr

Dalibor Brnobic
Studio elektronike Rijeka
Rijeka, Croatia
dalibor.brnobic@ster.hr

Renata Rubeša
Croatian Transmission Operator, HOPS
Zagreb, Croatia
renata.rubesa@hops.hr

Marko Rekić
Croatian Transmission Operator, HOPS
Zagreb, Croatia
marko.rekic@hops.hr

***Abstract*—Croatian TSO has finalized a Proof of Concept (PoC) for monitoring generators with purpose of primary frequency regulation mode within Wide Area Monitoring System (WAMS) using synchrophasors in control room. The main goal of PoC was testing well proven synchrophasor technology for purposes of advanced monitoring of generator units connected to transmission network. This technology was tested on six generators connected to 220 kV and 110 kV transmission network in five power plants. For this project three different ways of acquiring synchrophasor data for analyses were used. Data were collected with phasor measurement units (PMU) and from archives. Some PMUs were already installed on high voltage side of step up transformer earlier for other purposes, rest of measurement campaign was done using portable PMUs in two power plants. Results show full potential of using this data for monitoring generator for primary regulation. Output from project gives Croatian Transmission system operator (TSO) possible technical solution which can be implemented in control room.**

Keywords—frequency primary regulation, monitoring generator modes, PMU, synchronized phasor measurement WAMS

I. INTRODUCTION

Imbalance between production and consumption causes deviation of frequency from its nominal value in the synchronously connected power system such as continental transmission network. First stage compensation of such frequency deviation is done by primary frequency regulation. According to network code for transmission network [1], each generation unit has to be able to participate in primary frequency control and each control area is obliged to have this primary regulation reserve to contribute.

The status of primary regulation is very hard to detect with conventional measuring technology. To solve that problem high sampling frequency with time synchronized measurements is applied as a solution. This paper will elaborate monitoring of the primary regulation based on the synchrophasor measurements from WAMs and analysis of some generator primary regulator statuses in the Croatian power system. It is expected that this high sampling measurement will record any kind of transient phenomena on generator unit, contrary like SCADA or others measurements with sampling rate period higher than 1 second.

PoC has been conducted to check a possibility for monitoring generators in real time in control room with synchrophasor technology. Few typical generators were analyzed in PoC, one thermal unit and five hydro units. Units were monitored in all operating ranges and also some archived data was included in this document. This synchrophasor technology also successfully logs everything that happens during generator operations.

Croatian TSO placed PMUs on high voltage of step up transformer, Fig. 1. In those cases, it was 220 kV and 110 kV.

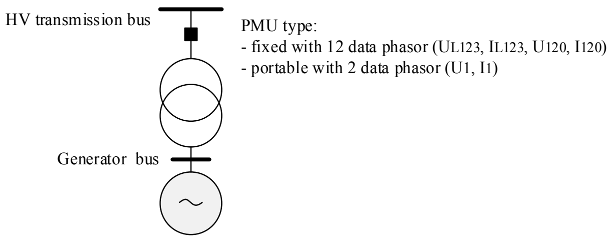

Fig. 1. PMU connection point on generator unit.

Two kind of PMUs were used in PoC, fix mounted standard TSO multifunctional PMUs, which create 12 synchrophasor data streams to control room (3phase values for voltages and current, and 3 sequence values for voltages and current). Second PMU type was portable type, which was used for measuring campaign for 6 months on two generator units in two hydropower plant. It creates only two synchrophasor data streams with positive sequence voltage and current.

Synchrophasor technologies have very high sampling rate resolution (20 ms) for measurement of frequency and active power, with same time stamps which makes those values comparable and applicable as a new functionality in WAMS.

TSO has obligation to determine primary regulation mode for each generator and this technology gives possibility to have full insight of generator unit operation. Slope characteristic of f/P diagram, can be monitored in real time from minutes to daily basis, or any other wanted period.

Generators on high voltage step up transformers side will be equipped with PMUs. In some cases, virtual PMUs for generators connected on busbar can be designed, if all other

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bays in switchyard has PMU. This case is not elaborated in PoC, as analyses are still being performed.

II. Frequency Primary Regulation in ENTSO-E

European Transmission System Operator for Electricity (ENTSO-E) is responsible for operational rules and security of high voltage transmission network among whole of Europe.

Any imbalance in power system for continental European transmission network in normal condition and during minor or medium disturbance will be compensated first with primary regulation and consequently with secondary or tertiary type of frequency regulation, depending on severity of disturbance Fig. 2. Each TSO is responsible in case of frequency deviation to compensate that frequency deviation, with generator units in operation [2]. Those units has to be declared and certified for that functionality, from TSO.

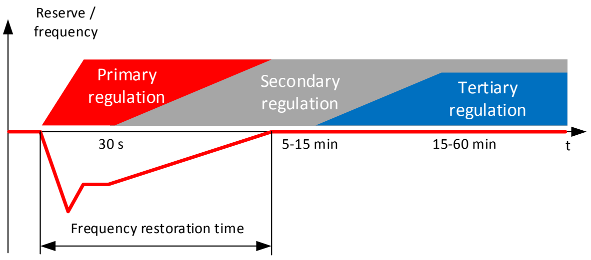

Fig. 2. Time frame for respond of primary, secondary and tertiary frequency regulation.

Primary regulation mode in continental European transmission network interconnection should be activated in first 15 seconds with range from 0 – 50% reserve, and from 50-100% in the next 15 seconds (total time is 30 seconds). Primary regulations has two main set points, first at frequency deviation of ±20 mHz and second is ± 200 mHz.

Generation Company should have units, which are available to operate in primary regulation within some range. Those data such as available power for primary regulation, respond time and droop speed control (statism) have to be recorded and monitored, from TSO's side.

TSO contribution for primary regulation reserve is mandatory and it is calculated for each year (1) in ENTSO-E coordination [3].

$$P_{i,c} = FCR_{interconnection} \cdot \left(\frac{G_{i,y-2}+L_{i,y-2}}{G_{u,y-2}+L_{u,y-2}}\right) \qquad (1)$$

Where are:

- $P_{i,c}$ – TSO initial obligation for primary regulation in current year,
- $FCR_{interconnection}$ – calculated value for primary regulation in whole interconnection,
- $G_{i,y-2}$ – electrical energy generation on TSO control area in two years before,
- $L_{i,y-2}$ – electrical energy consumption on TSO control area in two years before,
- $G_{u,y-2}$ – electrical energy generation for whole interconnection in two years before,
- $L_{u,y-2}$ – electrical energy consumption for whole interconnection in two years before.

Calculated primary regulation obligation for European TSO [4], in ENTSO-E interconnection for 2019, is given in Table I.

TABLE I. Calculated Primary Regulation

State	[MW]
ALB	4
AUT	66
BIH	15
BEL	80
BUL	41
SUI	61
CZE	81
GER	605
DEN (west)	20
ESP	368
FRA	527
GRE	46
CRO	11
HUN	29
ITA	274
MNE	2
MKD	5
NED	111
POL	157
POR	54
ROU	60
SER	39
SLO	15
SVK	26
TUR	294
UKR (west)	9
Total:	**3000**

This value of reserve has to be maintained during the whole year. In order to do that TSO has to have careful planning procedures with Generation Companies.

III. Monitoring with Phasor Measurement Unit

For proper detection of any changes in generation unit output it is necessary to have high sampling rate measurement and also that two measurements, of frequency and active power are synchronized, in order to be able to compare those two measurements. This measurement must be very sensitive and without dead zone, otherwise wrong picture of primary regulation operation can be deduced if there is a small change of operating point in a band of ± 20 mHz.

WAM system was used in this PoC like platform in control room. WAM receives and archives data from six generators unit in PoC with sampling rate of 20 ms [5], [6], [7], [8]. Those two measurements are compared for every frequency change. Active power output of generator unit must follow frequency change and give support to frequency recover [9], [10], [11]. In that case, that particular unit is active in primary regulation.

Droop speed control characteristic for generator unit active in primary regulation (2) is define:

$$\text{droop speed control} = \frac{\frac{\Delta f}{f_n}}{\frac{\Delta P}{P_n}} \cdot 100\% \qquad (2)$$

Where are:

- Δf – frequency deviation from nominal frequency,
- f_n – nominal frequency,
- ΔP – active power deviation from nominal value for generator unit,
- P_n – nominal power for generator unit.

Droop speed control on generator unit is given in relative values (%) for nominal frequency and active power value, and general characteristic is defining with f/P graph, Fig. 3, (frequency/Power).

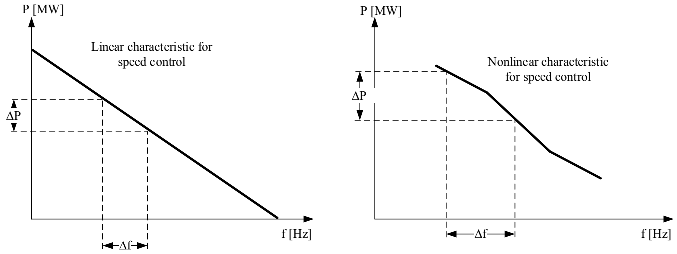

Fig. 3. Linear and non linear characteristic for droop speed control on generator unit.

Characteristic describe changes in active power output for generator unit according to frequency change in the system. Generator unit output will be changed according to characteristic, [12] [13] [14] which can be set like linear or nonlinear, Fig. 3.

Main goal of PoC is to get this characteristic with synchrophasor data for monitored generator units in different operation mode. Also, this characteristic must be able to present in few time scale:

- Minute (it is base for this PoC),
- Hour,
- Day,
- Month,
- or some other period.

PMU recorded frequency and active power and those synchronized measurements are then transferred to f/P characteristic, Fig. 4.

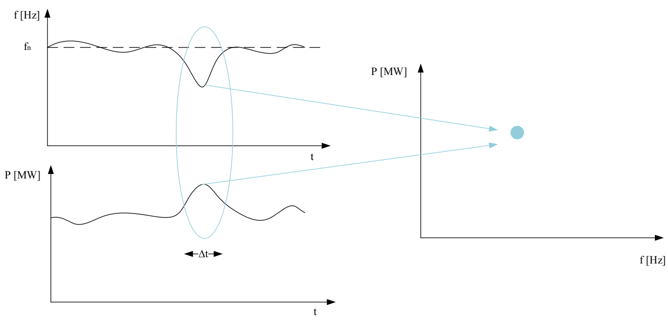

Fig. 4. Frequency and active power measurement with relation to f/P charcteristic.

In this PoC, f/P diagram was created based on average values of 1-second interval. One dot on f/P diagram, Fig. 4, presents this interval, and with more dots f/P diagram from Fig. 3, will be established.

IV. Generators Operated in Frequency Primary Regulation Mode

Hydro power plant Peruca (southern part of power system) has two generators equipped with fixed PMUs on 110 kV voltage level. HPP Peruca contributes for primary regulation with both generators unit. One detail is chosen for presentation how it is created on dot for f/P diagram. Fig. 5 presents short period (one hour) of operation for generator 2.

Fig. 5. f and P trends for generator 2 in Hydro PP Peruca with active frequency primary regulation in period 20:45-21:45 with marked detail in 21:02.

Detail of frequency deviation at 21.02 hours and proportional active power contribution is shown as point (red circle on left hand side on figure), Fig. 6, where deviation was at its maximum.

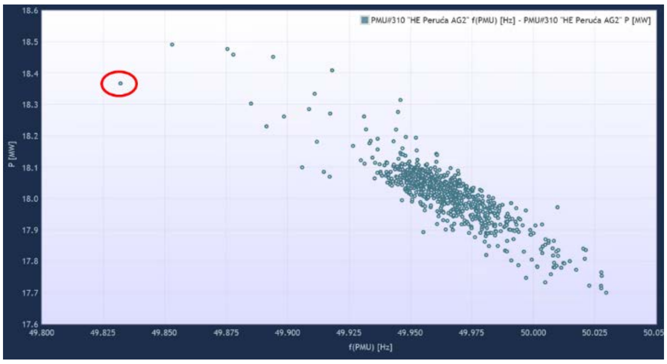

Fig. 6. f/P diagram for generator 2 in Hydro PP Peruca with active frequency primary regulation in period of 12 hours with marked detail in 21:02.

Taking in analyses all data on graph from Fig. 5 and Fig. 6 it can be noticed that there is a slight slope (or bias) which actually gives draw of primary control setting for generator unit. Great benefit for that is giving this data and graph in almost real time in control room or in back office for other business processes.

This technology can trace generator unit in all operation modes, from steady state to some small disturbances like, Fig. 5 in real time and in exact manner. In the next example it will presented longer period (almost 12 hours) of reporting than in this case.

Fig. 7 presents operation for generator 2 for 12 hours with this significant detail of frequency deviation (49.830 Hz) and outline of droop speed control characteristic, can be seen. Frequency and active power measurements for these 12 hours for generator 2 is on Fig. 7.

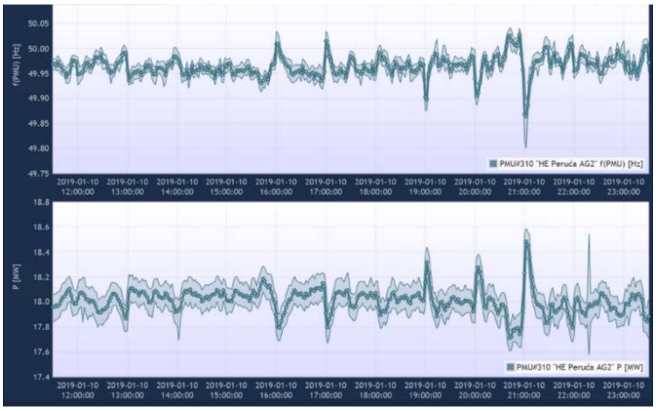

Fig. 7. f and P trends for generator 2 in Hydro PP Peruca with active frequency primary regulation in period of 12 hours.

Both generators units in HPP Peruca have activated primary regulation mode and clear outline of droop speed control characteristic for period of two weeks is created on Fig. 8.

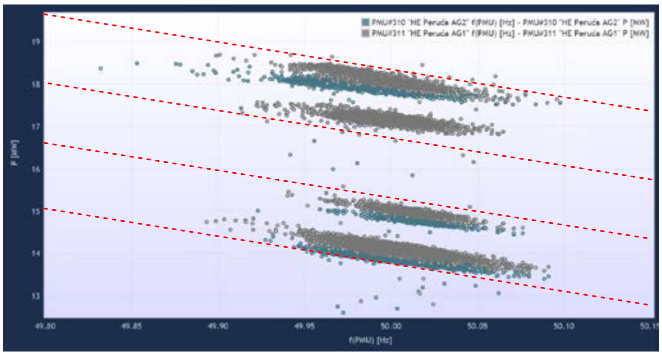

Fig. 8. f/P diagram for generator 1 and 2 in Hydro PP Peruca with active frequency primary regulation in period 03.01.2019.-17.01.2019.

Results from HPP Cakovec (northern part of the power system) equipped with portable PMU are also very good. Portable PMU a placed on 110 kV, for six month during measurement campaign.

Fig. 9 presents measurements for four hours with two different operational point for generator 2 with different active power output.

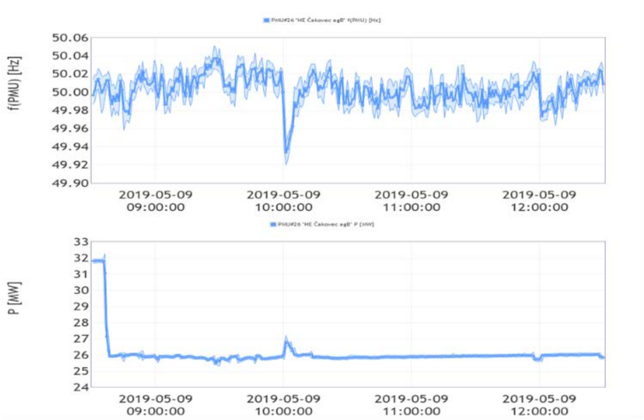

Fig. 9. f and P trends for generator 2 (B) in Hydro PP Cakovec with nonactive frequency primary regulation in period 09.05.2019. 08:30-12:30 hours.

Diagram f/P for this data in the same period, tracked accurately the both operating point, Fig. 10.

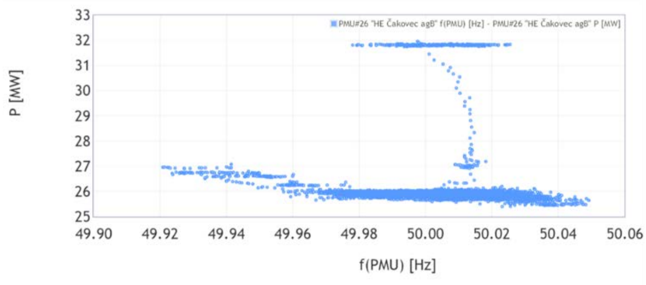

Fig. 10. f/P diagram for generator 2 (B) in Hydro PP Cakovec in period 09.05.2019. 08:30-12:30 hours.

This method also completely monitors generator unit in all operations mode.

During this period frequency dropped on 49.92 Hz and power output increased for 1 MW, Fig. 11. On that data f/P diagram was formed where activation of primary regulation for under and over frequency deviations will be seen.

This case shows big potential for using synchrophasor data because it can very accurately trace all small changes on generators operations and give full insight for generators responds on network events and disturbances.

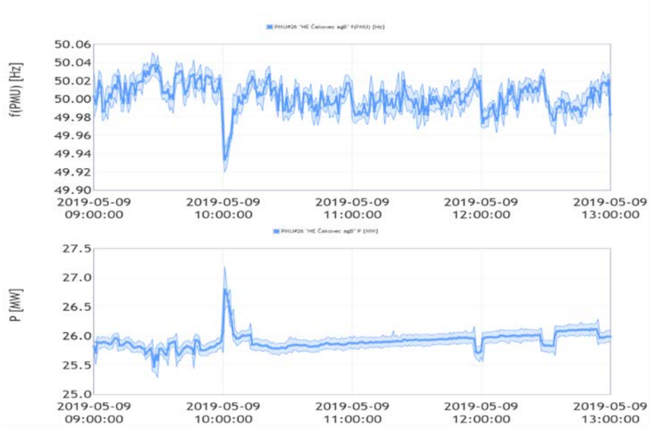

Fig. 11. f and P trends for generator 2 (B) in Hydro PP Cakovec in period 09.05.2019. 09:00-13:00 hours, with significant frequency drop.

Detail from f/P diagram in frequency range from 49.92 Hz to 50.05 Hz, for generator 2 in HPP Cakovec present dead band for ± 20 mHz, Fig. 12. In addition, the outline for primary regulation characteristic are created (with red dashed line). This kind of graph will be in future technical solution automatically created.

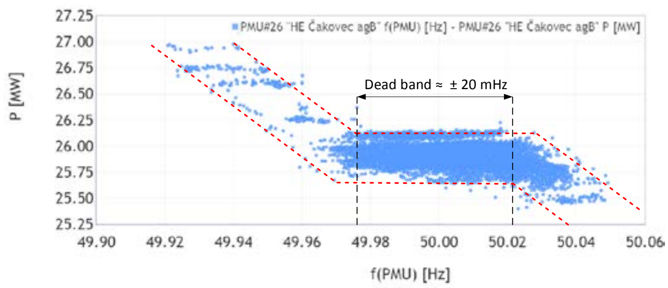

Fig. 12. f/P diagram for generator 2 (B) in Hydro PP Cakovec in period 09.05.2019. 09:00-13:00 hours, with significant frequency drop.

It is possible to get report for generators response and regulation set up for dead band zone with synchrophasor data.

V. GENERATORS WITH SWITCHED OFF FREQUENCY PRIMARY REGULATION MODE

This PoC used also archives synchrophasor data for analyses. HPP Dubrovnik has many recorded data, which will present response of generator unit 2 for primary regulation. Generator 2 has fixed PMU on 220 kV level.

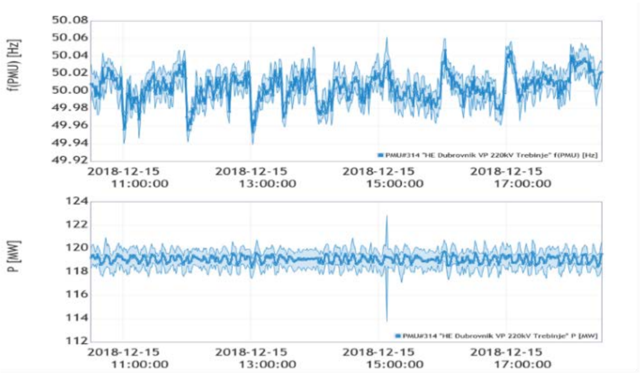

Fig. 13. f and P trends for generator 2 in Hydro PP Dubrovnik in period 15.12.2018. 10:30-18:30 hours.

Fig. 13, presents frequency and active power output in a period of 8 hours at 15.12.2018. It was stable generator operation without significant frequency deviations. Frequency change was from 49.94 Hz to 50.04 Hz. Some small changes were recorded on active power output. At the end f/P diagram gives outline for generator characteristic, Fig. 14.

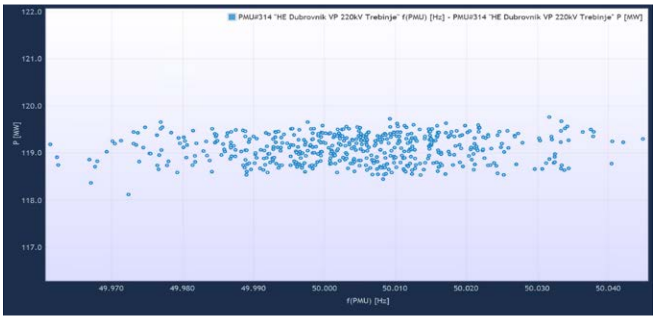

Fig. 14. f/P diagram for generator 2 (B) in Hydro PP Dubrovnik with nonactive frequency primary regulation in period 09.05.2019. 09:00-13:00 hours.

Creating the f/P diagram gives quick and very accurate insight of operation mode for particular generator. In this case, only two hours period was analyzed in detail manner.

Generation Companies can change as matter of fact setting point for each generator unit during one day in order to give services of primary frequency control.

VI. CONCLUSION

PoC was based on usage of standard tools and standard equipment used in Croatian TSO, which gives good and promising results for future use in area of frequency primary regulation monitoring.

For TSO is very important that those tools use noninvasive technique of measurement on generator units due to them being an asset of Generation Company.

Six generators were uses for analyses in this PoC to see their respond and possibilities to contribute for frequency primary regulation. In paper were presented some characteristic results for four generators unit.

Noninvasive technology with PMUs data collecting and creating f/P diagram gives very good and detailed reports for different time horizon.

Future work in Croatian TSO will be to define solution for frequency primary regulation monitoring in WAM system in control room. Technology is well known and the future server architecture will be created in order to generate reports for that kind of monitoring.

With such solution TSO and Generating Companies as well, will have powerful tool to trace all generating units for various business processes.

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