Frequency and Voltage Stability Assessment of a Power System during Emergency Service States

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***Abstract*— Emergency service states of an electric power system such as island operation, black start or fall in to a blackout are accompanied by rapidly increased requirements of system control and ability to withstand major power, frequency and voltage changes. This paper presents an example of an electric power system (basic connection of city of Pilsen on the 110 kV voltage level) falling in to an island operation and examines influence of rapid load/generation balance changes on the system frequency and voltage. It shows advantages and threats of Rate of Change of Frequency (RoCoF) application instead of solid frequency limits for both – protection of generators and Under Frequency Load Shedding (UFLS). The paper also deals with the question of decreased frequency and its influence on the connected load. (*Abstract*)**

Keywords*— frequency control; power system; island operation; emergency states; rate of change of frequency (key words)

I. INTRODUCTION (*HEADING 1*)

In the previous publications the possibility of island operation was discussed only in the view of frequency stability. The inertia equation describing mechanical and electrical behavior of the system was used and the change of frequency Δf was tracked as a decision parameter. The maximal frequency difference during the transition in to the island operation differs from each country.

This paper takes a closer look on the system during the transition also from the view of voltage and examines the first level of current setting of the Under Frequency Load Shedding (UFLS). Current approach to the first level of UFLS is compared to Rate of Change of Frequency (RoCoF) approach which seems to be a much more sophisticated tool than strict frequency limits as e.g. used in the Czech Republic. It might recognize the dangerous situation faster than limits given by currents settings and is intelligent enough to prevent the load from pointless disconnection when the frequency would stabilize after first 30 seconds of the primary regulation process. [5] [1]

II. POWER SYSTEM DESCRIPTION

City of Pilsen was chosen as an example power system thanks to its unique position in the power grid of the Czech Republic and the topic of island operation is actively solved for last several years. The transition in to the island operation is performed firstly on a frequency model and then on grid model using the MATLAB PSAT toolbox.

III. SIMULATION

A. Frequency model

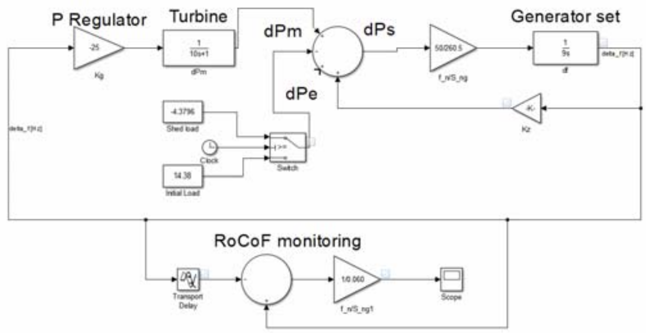

Fig. 1. Frequency model of hypothetical island in Simulink

Basic model of the power system is used for the description of frequency dependence on the changing power. The limitation of the maximal power change is neglected for a better illustration of the solved topic. The self-regulation of the connected load is considered. Mechanical time constants are $T_m = 9s$, $T_T = 10s$. The amplification of the P regulator is $-25\ MW/Hz$. In the lower part of the model is situated the RoCoF monitoring. Following figure shows the development of frequency change after system split for different ΔP.

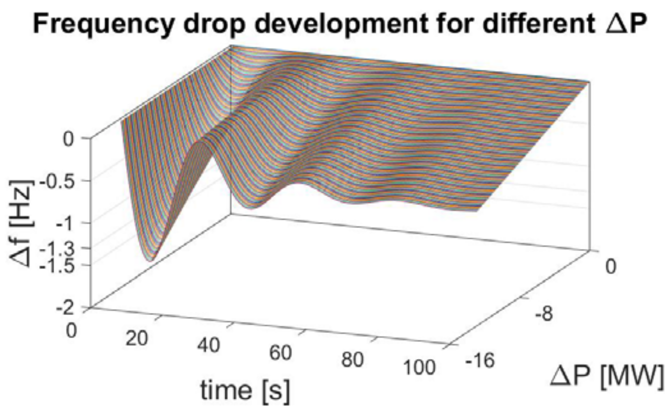

Fig. 2. Frequency model of hypothetical island in Simulink

The basic frequency model is accurate enough to describe the solved situation of frequency change in the electrical island during its transition being in speed control mode.

B. Model in view of voltage

The model for purpose of voltage monitoring during the transition in to island operation is created in MATLAB toolbox PSAT.

The model consists of a power system with 12 buses representing 110/22 kV substations in city of Pilsen (hypothetic electrical island). PV nodes are used for representing the power sources and negative PQ nodes are used for representing the connected load. The slack bus is placed inside the power grid in the most remote place from the sources. It cannot be placed outside the island to connection to 400 kV because during the disconnection of the island the simulation would stopped. The interconnection lines on 110 kV level are represented by a pi type model of a three phase transmission line. Because of confidentiality of the data, the input parameters for this paper are chosen respecting the needs of objectivity of results. The model is visible in the picture below.

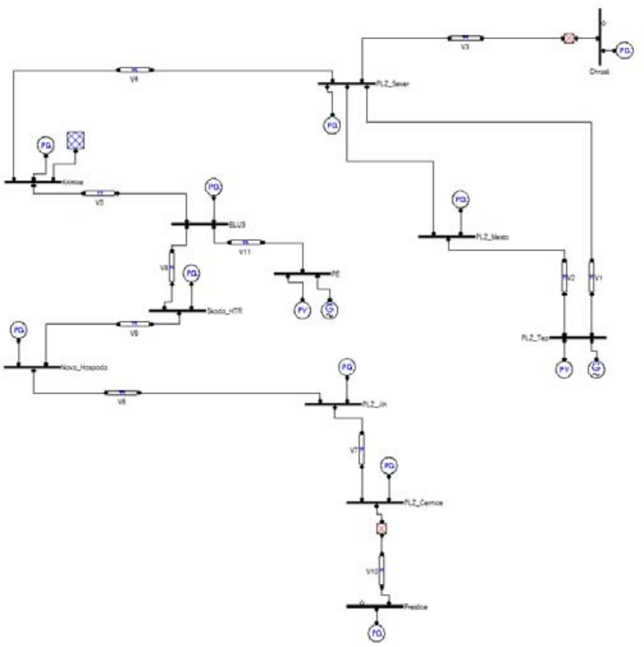

Fig. 3. *Model created for voltage monitoring in PSAT toolbox in MATLAB*

It is possible to examine the power flow in the steady state of the hypothetical island but also the transient state during the transition in to the island operation. It is very probable that for example city of Pilsen would be divided in to two smaller island each connected to its source (approximately 110 MW and 150 MW) but this scenario is not solved in this paper.

IV. RESULTS

A. Frequency control

In the following picture are visible two situations of the hypothetical electrical island. First (blue) – the frequency stays above the first level of UFLS and stabilizes after approximately 60 seconds on the level 49.6 Hz. In this case the active power imbalance ΔP is 11.07 MW representing a change of 4.2% of the installed power in the chosen island power system.

During the second situation (red) the frequency dips under the first level of UFLS reaching almost the second level (48.7 Hz). After approximately the system stabilizes after 60 seconds on the “safe” frequency level of 49.45 Hz. The active power imbalance ΔP is in this case 14.38 MW representing a change of 5.5% of the installed power.

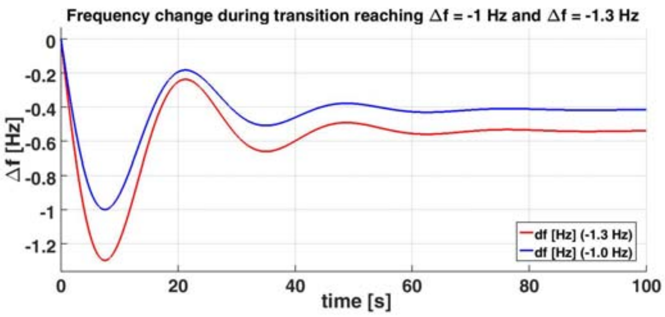

Fig. 4. Frequency change during transition in to island operation

Both situation have in common the fact that frequency stabilizes after approximately 60 seconds above the level of 49.2 Hz which is globally considered as safe during emergency situations such as island operation. In the red case the frequency is under 49.0 Hz for not more than 7.9 seconds but from the view of the steady state may be considered as a safe.

The following figure shows a situation when the first level of the UFLS is triggered immediately after reaching the 49.0 Hz level. Immediate triggering is given by the TSO Grid Code.

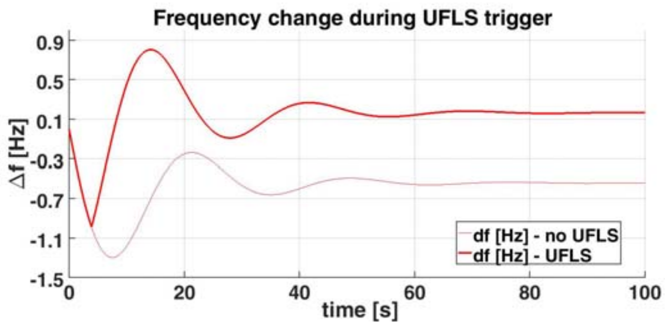

Fig. 5. Frequency change during transition in to island operation

It is visible that the frequency jumps immediately after the shedding first 12% of connected load (18.76 MW) in selected 110/22 kV substations. It is obvious that the UFLS prevents the system from further frequency fall but on the other hand from the view of steady state both situation (with or without activation of the UFLS) are in this case safe. Even the situation with UFLS activation represents greater stressing of the rotating machines thanks to greater frequency changes. [5]

The following figure shows the shape of RoCoF monitoring during the frequency change without UFLS triggering for the same active power difference as in Fig. 5.

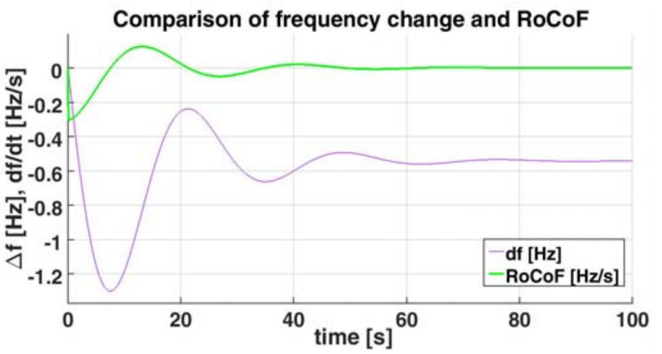

Fig. 6. Frequency change and RoCoF

The commonly considered limits for RoCoF in ENTSO-E are

- 0.2 - 0.5 Hz/s (max. 500ms)
- 1 Hz/s (max. 500ms)
- 2 Hz/s (max. 500ms)

Because of unknown behavior of the chosen system the first criteria is selected as applicable in the case of transition in to the island operation. This criteria (0.2 – 0.5 Hz/s over max. 500 ms) is used in system with untested ability of the sources to withstand the quick change of frequency. From the Fig. 5 is visible that the value of RoCoF (green line) stays within the limits given by the first criteria if the value of maximal RoCoF is greater than 0.3 Hz/s. The RoCoF measurement is given by the following formula: [3] [5]

$$\frac{df}{dt} = \frac{f_n - f_{n-3}}{T_{3cycles}} \; [s; MVA; Hz; MW]$$

If newer certified sources would be chosen, the criteria might be higher (up to 2 Hz/s). It is obvious that use of RoCoF for load shedding instead the first level of UFLS on the level 49.0 Hz might be very useful because it can recognize the non-dangerous situations and lets the transient state reach safe frequency after approximately 10 seconds (see Fig. 5).

B. Voltage control

For the description of the power-flow before the system split and transition in to the island operation, the model in Fig. 2 was used. Following picture shows the visualization of voltage across the model in steady state before the system split.

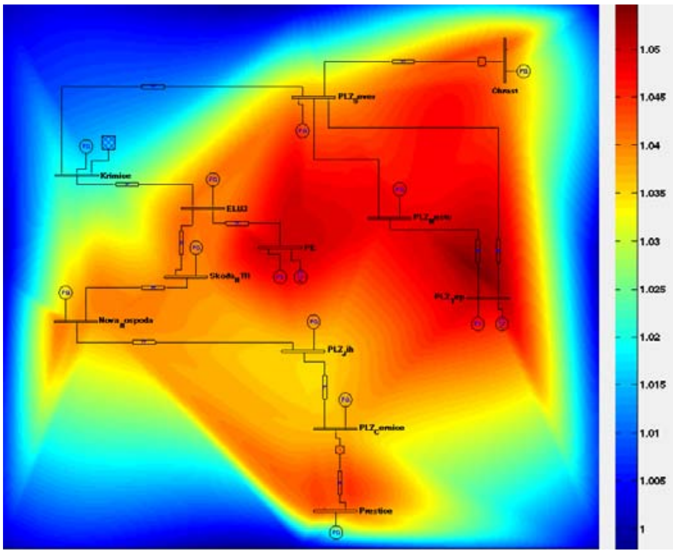

Fig. 7. Voltage magnitudes of the chosen power system – Pilsen (110 kV)

It is visible that the voltage magnitude rises in the substations near to the sources – *PLZ_tep* and *PE*. Also the voltage increases in substations that connect the city to the rest of the power system of the Czech Republic. The interconnection of city is only chosen as one of the possible and differs from the normal operational state.

Following picture shows steady state voltage distribution when the city is disconnected from one of the connection points to the TSO. It is visible that the voltage drops by 5% when the city is disconnected from the transmission system supply in the south part (substation *Prestice 400/110 kV*). This state doesn't represent a threat in the view of solved topic.

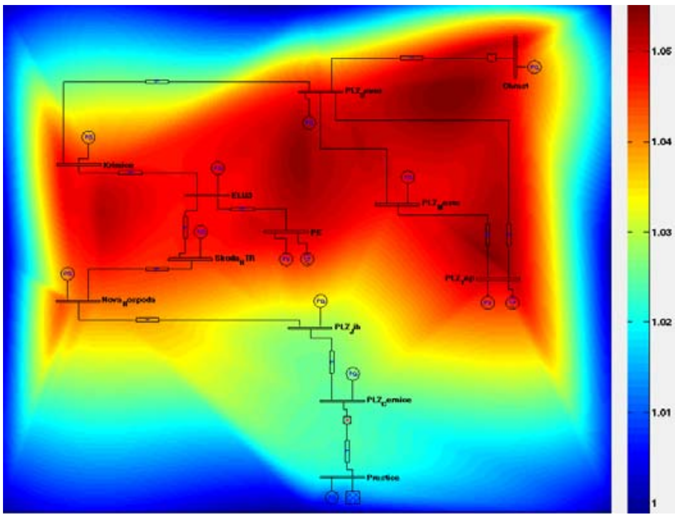

Fig. 8. Voltage magnitudes of the chosen power system – Pilsen (110 kV)

In the table below are displayed power flows between 110/22 kV substations in the hypothetical interconnection of the island. The chosen consumptions does not represent the real state and are shown for purposes of this paper.

TABLE I. POWER FLOWS IN THE STEADY STATE BEFORE ISLAND OPERATION

From Bus	To Bus	P Flow	Q Flow
		[p.u.]	[p.u.]
PLZ_Tep	PLZ_Sever	**0,42**	0,34
Prestice	PLZ_Cernice	0,10	0,03
PE	ELU3	**0,67**	0,40
PLZ_Tep	PLZ_Mesto	**0,33**	0,08
Chrast	PLZ_Sever	0,05	-0,46
PLZ_Sever	Krimice	0,33	-0,16
ELU3	Krimice	-0,08	0,22
PLZ_Jih	Nova_Hosp	-0,27	-0,06
PLZ_Cernice	PLZ_Jih	-0,02	0,00
Skoda_HTR	ELU3	-0,49	-0,11
Skoda_HTR	Nova_Hospo	0,28	0,05

It is visible from the table above that the generation that is situated in the substation that are highlighted is equal to 140 MW resp. 54.5% of the installed electrical power in generation. Connections "*Chrast – PLZ_Sever*" and "*Prestice - PLZ_Cernice*" represent the interconnection with the TSO. These two buses represent the import of electrical energy in to the island system and it is equal to approximately 15 MW. This amount of power is disconnected during the system split and causes the transient state in Fig. 3-5.

The following picture shows the change of voltage magnitudes in 110 / 22 kV substations during the transition in to the island operation. Corresponding to the frequency change transient states, the voltage stabilizes roughly after first 10 seconds of the system split. From the view of the system voltage stability this type of transition (Fig. 3 – red line) does not represent a threat that would cause voltage oriented protections to operate.

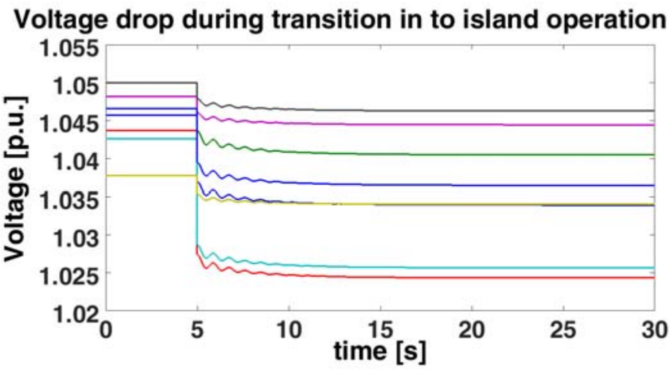

Fig. 9. Voltage change on 110/22 kV substations during transition

The previously described model seems to be more suitable for the possibility of power flows examination and is very useful for overload-check during specific interconnection configurations of the islanded system. Currently is under development for the frequency control and verification purposes.

V. CONCLUSION

Goal of this paper was to create an overview of two currently used methods for frequency shedding. First – frequency limit-based UFLS is commonly used as a tool for prevention of a frequency fall in a splitting or split power system. It is a very stable and easy tool giving a 100% guarantee of further frequency fall reduction in cases such as presented in figures above. On the other hand it might not recognize situations that are not dangerous from the point of frequency control and additionally may add rotating machines stressing and also useless consumer discomfort represented by strict UFLS disconnection.

The RoCoF approach to UFLS is more sophisticated and its integration in to the first level of the UFLS would bring more comfort to the user but still an ability to recognize dangerous situation when the frequency fall is too steep and might lead to reaching second level of the UFLS which must remain defined as it is nowadays. Generally a 5-6% active power imbalance between the island power system and the rest of the grid might be accepted as safe. The conditions of the safe transition in to the island operation must be solved further.

Hand in hand with nowadays trends of decentralization of the generation, the topic of small island operations as a tool for emergency states solution will be a frequently discussed question. Short frequency decline in micro power grids such as smart villages or rural regions with absence of big frequency dependent load can survive situation such as in Fig. 5 without the need of disconnection and threat of dangerous stressing given by fast frequency changes.

ACKNOWLEDGMENT

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REFERENCES

[1] Rate of Change of Frequency (ROCOF) Review of TSO and Generator Submissions Final Report. PPA Energy, 2013.

[2] Rate of Change of Frequency (RoCoF) Modification to the Grid Code. The Commission for Energy Regulation, Dublin, 2014.

[3] Rafał Bugdal, Adam Dyśko, G.M. Burt, J.R. McDonald. Performance analysis of the ROCOF and Vector Shift methods using a dynamic protection modelling approach. Glasgow, 2006.

[4] Dr Adam Dyśko, Dimitrios Tzelepis, Dr Campbell Booth. Assessment of Risks Resulting from the Adjustment of ROCOF Based Loss of Mains Protection Settings. Glasgow, 2015.

[5] Rules for Transmission System Operation - Grid Code. Prague: CEPS a.s. (TSO), 2016.

[6] J. HAJEK, Prechodne jevy v elektrizacnich soustavach. Pilsen: Edicní stredisko VSSE. Czech Republic, 1983.

[7] P. KUNDUR, Power system stability and control. McGraw-Hill, Inc., 1993. ISBN: 978-0070359581.