Defining the power system load frequency static response slope based on transient synchrophasor data

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Abstract. The method is proposed for defining the power system load frequency static response based on synchrophasor measurements during transients accompanied by frequency deviations. The method was successfully validated involving four events resulting in frequency deviations in the Northern part of Tyumen region of up to 0.06 Hz magnitude and recorded by means of the System operator WAMS.

1 Introduction

Frequency and active power changes in bulk power systems are characterized by a power system or a power region active power frequency static response. Resulting power system response depends upon the corresponding response of the generation and the loads [1].

Different from the nodes load voltage static response for a power system or a power region, load frequency static response might be derived only as an aggregate of the nodes responses. It is due to the fact that load nodes voltage is a locally controlled parameter while the frequency might be assumed similar or close to similar for all power region nodes at any time.

Power region aggregate load is defined as the sum of the region generation and net external power flow:

$$P_{\text{load}}(t) = P_{\text{gen}}(t) + P_{\text{flow}}(t) \tag{1}$$

However, not all generation sources provide frequency and power measurements, that is generally applicable to low-capacity generation, mostly distributed (distributed energy resources, DER).

Hence, due to the impossibility to measure overall generation and evaluate the actual influence of the nodes voltage on their consumption, the aggregate power region static response is to be considered, being characterized by the load value.

What should be noted here is the importance of the frequency static response slope. Frequency static response is an inherent parameter of a power system computational model along with other parameters. Utilizing the power system computational model enables the calculation of power system operation conditions, which serve as the basis for solving the power system dispatch control tasks, such as defining the admissible power flow over the power system sections, required minimum generation capacity margins, effectiveness of automatic control actions etc. [3, 4, 5] In case the actual frequency static response is unknown, the computational model parameters are defined based on rated values with the most undesirable values being considered in order to ensure the results account for the heaviest power system operation conditions. If the frequency static response is better than the assumed, this leads to excessive power system operation restrictions, which, in turn, reduces the overall power system efficiency.

In 1970s-1980s frequency and voltage static response as well as frequency static response slope for the load nodes with different consumption mix were defined experimentally involving actual power systems in operation. To date conducting these experiments is difficult and expensive, moreover, their consequences are unpredictable [1, 6]. Hence, the existing frequency static responses have become obsolete due to significant changes in consumption structure and steadily widening variety of load components (storage systems, electric vehicles, etc.).

The introduction of the new generation measurement devices, providing the possibility to obtain the time-synchronized high-accuracy measurements of power and frequency corresponding to the external power flows and high-capacity generators, allows to define the external power flows and generators frequency static response based on the transient recordings during regular operation (i.e. conduct passive experiments) under random disturbances conditions in power system. Current work proposes the investigation of the possibility to define a power region or a load node frequency static response slope based on the transient recording corresponding to the predefined short periods of time:

$$P_{\text{load}}(t, f) = P_{\text{gen}}(t, f) + P_{\text{flow}}(t, f). \tag{2}$$

2 Defining load frequency static response slope

The methods and algorithms have been developed in order to define and monitor the response based on the actual recordings of the power system performance parameters in the nodes equipped with PMUs under deviating frequency and voltage conditions in a load node driven by disturbances of the following types:

- emergency generation or load trip;
- external grid parameters change (transmission line or generator trip);
- load terminals or external grid fault;
- several seconds power outage (automatic supply restoration delay);
- out-of-step operation;
- low-frequency oscillations.

Hence the nodal load static and dynamic response can be defined under changing voltage and/or frequency conditions $\{P_{load}(U), Q_{load}(U), U(t), f(t), P_{load}(t, U), Q_{load}(t, U)\}$ along with the performance parameters mutual influence $\{P_{load}(U, dU/dt), Q_{load}(U, dU/dt), P_{load}(f, df/dt), Q_{load}(f, df/dt)\}$.

Defining the interconnection between various monitored parameters is based on the modified Gauss technique [7].

The aggregate power system or single node frequency static response is evaluated by identifying the expression parameters on a simulation time period t_m based on the active power and frequency measurments:

$$P_{load}(t_i, f(t_i)) = a_0 + a_1 t_i + a_2 t_i^2 + a_3 f(t_i) + a_4 f^2(t_i), \quad (3)$$

where $t_i \in T_m = \{t_1, t_2, ..., t_m\}$;

$f(t_i) \in F_m = \{f(t_1), f(t_2), ..., f(t_m)\}$;

$P_{load}(t_i, f(t_i)) \in P_m = \{P(t_1, f(t_1)), P(t_2, f(t_2)), ..., P(t_m, f(t_m))\}$.

By differentiating the expression with respect to frequency, one can obtain $\partial P_{load} / \partial f = a_3 + 2a_4 f(t_i)$, and hence

$$k_{si} = (\partial P_{load} / \partial f)(f_b / P_b) = (a_3 + 2a_4 f(t_i)) f_b / P_b, \quad (4)$$

where P_b, f_b – active power and frequency basis values.

Load frequency static response slope k_s for a single node can be derived by taking into account the voltage values at the node corresponding to the simulation time period:

$$P_{load}(t_i, f(t_i), U(t_i)) = a_0 + a_1 t_i + a_2 t_i^2 + a_3 f(t_i) + a_4 f^2(t_i) + a_5 U(t_i) + a_6 U^2(t_i) \quad (5)$$

Then the load derivative with respect to frequency is:

$$\frac{dP_{load}}{df} = a_3 + 2a_4 f(t_i) \quad (6)$$

Under small frequency deviation it is feasible to reduce the expression to linear components and assume the load change over time to be insignificant, therefore (3) can be written over as follows:

$$P_{load} = a_0 + a_3 f(t_i), \quad (7)$$

and

$$\frac{dP_{load}}{df} = a_3. \quad (8)$$

Then the frequency static response slope k_s, according to [1] and (4), is expressed as

$$k_s = a_3 \frac{f_b}{P_b}. \quad (9)$$

3 Case study

Current research presents the example of utilizing the proposed technique for defining the frequency static response slope of one of the Ural interconnection power regions.

3.1 Cases background

The majority of the region consumption is constituted by oil and gas industrial facilities, including refining, transport, waste handling, along with residential load.

The considered region is deficient in terms of active power. Its demand is partially met by several power plants and numerous CCGTs deployed at several oil and gas companies' production sites.

According to legal regulations [8], the governors controllers deadband must not exceed 0.3 % (which is ±0.15 % or, in case rated frequency of 50 Hz is assumed, ±0.075 Hz) [9]. Frequency deviations do not exceed 0.6 Hz in all considered cases. Moreover, since the region power plants do not participate in primary frequency control, their response to those deviations can be neglected. Therefore, the obtained frequency static response slopes reflect the actual load response to frequency deviations.

In case the investigated power system includes power plants involved into primary frequency control, their frequency response can be defined according to (2) if there are PMUs there. The monitored parameters (active power and frequency) were recorded for the complete section separating the considered region from the Ural interconnection. The base frequency and load power were assumed to be equal to, correspondingly, 50 Hz and the region consumption prior to the disturbance, according to the System operator SCADA data, with local generation taken into account.

The key issue of utilizing the frequency static response slope definition technique for the power system region at hand is the considered time period selection. Different periods of the recordings shown in Figures 1–5 were selected for the detailed investigation. The slopes defined for the whole transient are given in **bold** in tables.

3.2 02/24/2017 event

The first considered transient resulted from the disturbance, which happened February 24th, 2017. The active power and frequency plot is presented in Figure 1. Five indicative intervals were selected for the detailed analysis the pre-disturbance steady-state operation, the period of frequency drop to 49.93 Hz and its subsequent restoration to 49.99 Hz. The calculated frequency static response slope are summarized in Table 1.

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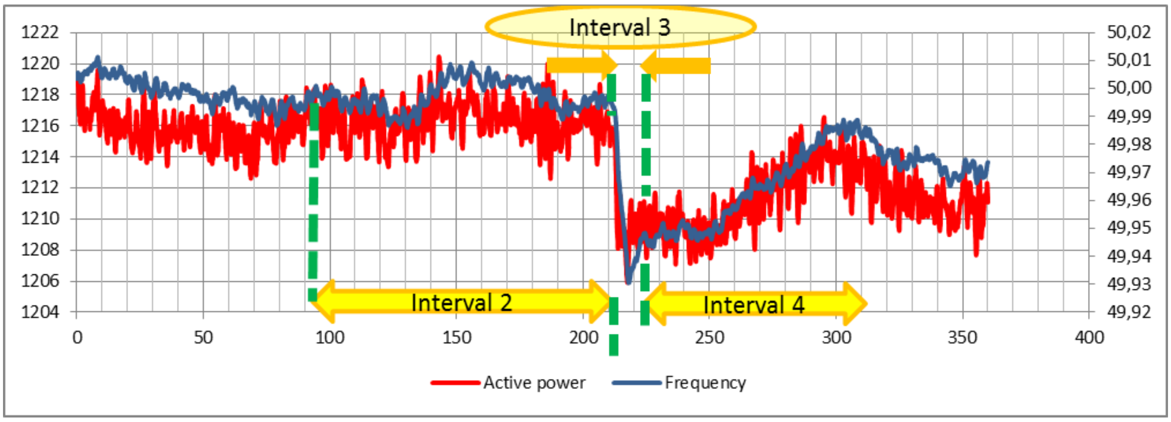

Fig 1. 02/24/2017 event, considered intervals

Table 1. 02/24/2017 event P(f) coefficients, P_b=2182 MW

Object	Int 1 100–300 s	Int 2 100–210 s	Int 3 210–220 s	Int 4 220–300 s	Int 5 212–214 s
Section aggregate	165.0	97.6	107.8	136.1	345.5
Line 1	88.2	36.4	66.2	96.2	186.3
Line 2	28.1	28.8	11.9	2.0	94.4
Line 3	12.6	5.9	7.7	3.6	19.6
Line 4	35.7	38.0	27.2	37.7	113.8
Section aggregate dP/df	165.0	97.6	107.8	136.1	345.5
Section aggregate response slope	**3.78**	2.24	2.47	3.12	7.92

3.3 06/27/2017 event

The next case comprises two sequential transient, which took place June 27th, 2017. The graphs showing the active power and frequency are shown in Figures 2 and 3. There are three distinctive intervals selected for the first transient – the pre-disturbance operation, the oscillatory transient and the complete process. The second transient is subdivided into two intervals: the oscillatory transient ant the complete process including the pre-disturbance state. The frequency static response slope calculation results are presented in Table 2.

Table 2. 06/27/2017 event P(f) coefficients, P_b=1856 MW

Object	Int 1 175–190 s	Int 2 173–179 s	Int 3 179–191 s	Int 4 1614–1622 s	Int 5 1615.6–1622 s
Section aggregate	138.0	68.6	156.3	189.8	186.5
Line 1	65.9	28.8	67.2	79.6	77.2
Line 2	35.9	12.7	43.2	41.6	39.6
Line 3	3.9	-0.1	4.9	9.2	10.2
Line 4	48.0	30.2	49.1	59.6	59.5
Section aggregate dP/df	138.0	68.6	156.3	189.8	186.5
Section aggregate response slope	3.72	1.85	**4.21**	5.11	**5.02**

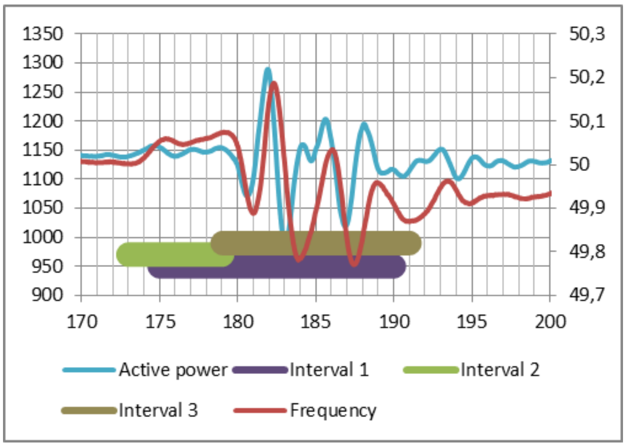

Fig 2. 06/27/2017 event (part 1), considered intervals

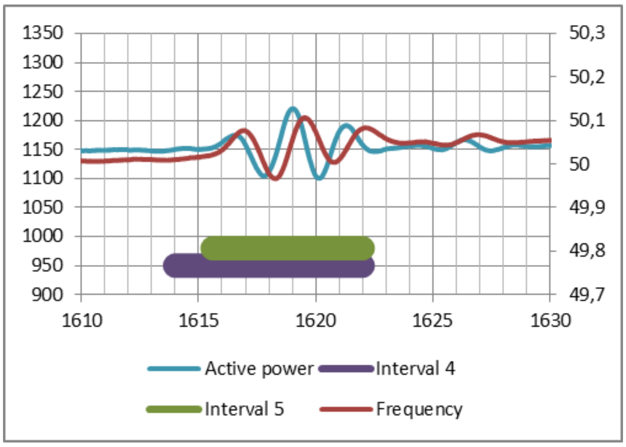

Fig 3. 06/27/2017 event (part 2), considered intervals

3.4 07/25/2017 event

The other considered transient is relatively long-standing, it took place July 25th, 2017. The recordings of active power and frequency are plotted in Figure 4. Three indicative intervals are selected for the analysis: the steady increase of frequency and its rapid drop by 0.08 Hz. The frequency static response slope calculation results are shown in Table 3.

Table 3. 07/25/2017 event P(f) coefficients, P_b=1764 MW

Object	Int 0 0–1200 s	Int 1 820–1160 s	Int 2 700–1160 s	Int 3 0–700 s
Section aggregate	142.7	184.3	184.3	55.0
Line 1	-83.3	-97.6	-97.1	-49.2
Line 2	-0.2	-19.2	-20.4	30.1
Line 3	-3.2	-5.0	-4.8	-0.9
Line 4	56.5	62.5	62.0	42.0
Section aggregate dP/df	142.7	184.3	184.3	5.0
Section aggregate response slope	4.05	**5.22**	**5.22**	1.56

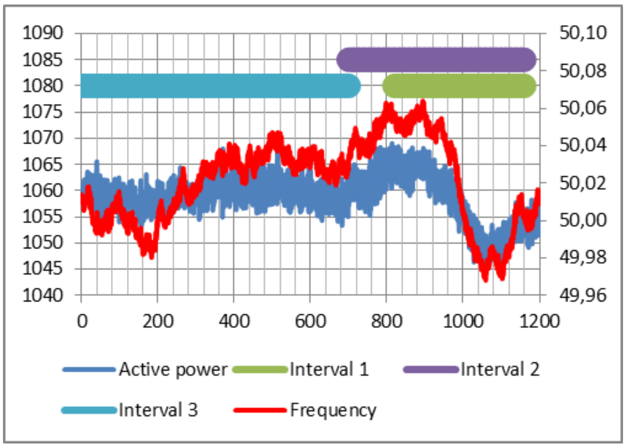

Fig 4. 07/25/2017 event, considered intervals

3.5 07/30/2017 event

The transient involving frequency deviation happened July 30th, 2017 is considered. The frequency and active power plots are shown in Figure 5. Four indicative intervals are selected for the analysis the pre-disturbance conditions, the period of frequency decrease to 49.94 Hz, the subsequent frequency restoration to its rated level and the combination of the last two intervals. The calculation results are shown in Table 4.

Table 4. 07/30/2017 event P(f) coefficients, P_b=1847 MW

Object	Int 1 0–1200 s	Int 2 0–400 s	Int 3 400–1200 s	Int 4 400–800 s	Int 5 800–1200 s
Section aggregate	154.8	80.7	137.6	161.1	137.6
Line 1	87.6	53.2	80.1	103.9	76.3
Line 2	8.9	5.0	6.0	-1.2	22.2
Line 3	3.7	2.2	4.0	2.3	4.9
Line 4	54.7	22.1	54.7	56.2	52.1
Section aggregate dP/df	154.8	80.7	137.6	161.1	137.6
Section aggregate response slope	**4.19**	2.18	3.72	4.36	3.72

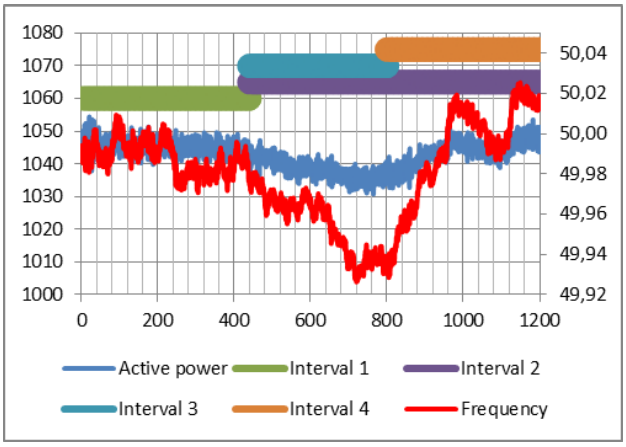

Fig 5. 07/30/2017 event, considered intervals

3.6 Case study summary

The case study results analysis is summarized in Table 5. Frequency static response slopes were selected from Tables 1–4 for the time periods corresponding to the whole transient in accordance with [6]. Overall consumed power is obtained from the System operator SCADA system for the moment prior to the considered disturbance.

Table 5. Frequency static response slopes, summarizing table.

Event	Load, MW	Response slope
02/24/2017 event	2182	3.78
06/27/2017 event (part 1)	1856	4.21
06/27/2017 event (part 2)	1856	5.02
07/25/2017 event	1764	5.22
07/30/2017 event	1847	4.19
Average		4.48

It can be seen from the table that the resulting frequency static response slopes defined for different time periods differ significantly. The value obtained for the only considered winter period (3.78) stands out from the overall range. In case it is not taken into account, the average slope equals to 4.66. at that, the value adopted in actual practical tasks is the same over the year and equals 5.

4 Conclusion

The proposed technique for defining the frequency static response slope has been validated using actual WAMS data for one of the Ural interconnection power regions under frequency deviations of up to 0.06 Hz. The results obtained for different time periods closely match, and the average slope is close to the one utilized in practical tasks. At that it is worth noting that partial time periods do not provide valid results, which renders their consideration undesirable for the corresponding task. On the contrary, one should be inclined to take into account the complete transient time period, which accords with [6] summary.

The future development of current research implies in-depth investigation using computational models and physical electrodynamic simulator equipped with PMU, with frequency static response being predefined, which makes the study environment totally controlled.

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