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Assessment of Power Lines Performance Based on Voltage Sag Indices

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***Abstract*—Power lines performance has traditionally been assessed in terms of their efficiency and reliability. The increase of the effect of voltage sags on sensitive loads may be located far away from the faulted line, claims for a new analysis of line performance. A new method to evaluate power lines performance is proposed and compared with the previous ones based on the power line reliability. The results show that the new method can change the ranking of line performance and therefore the utility focus for investment.**

***Index Terms*—power line performance, power quality, voltage sags, reliability.**

I. Nomenclature

DFR: Digital fault recorder
ΔP_i: Instantaneous load variation (MW)
ΔP_{av}: Average load variation (MW)
NSE: Non supplied energy (MWh)
CEMIG: Minas Gerais Utility Company

II. Introduction

THE performance of power lines is a great concern for utilities in deregulated power systems. There are several ways to understand the performance of a power lines. It can be defined in terms of efficiency and reliability of supply [1].

The performance of transmission systems under steady state operation was studied in terms of the transmission efficiency [2]. The active and reactive power at both sending and receiving ends of the system were evaluated and then the transmission efficiency was determined. The effect of the load impedance was studied and the resulting variation of the transmission capability was deduced.

The transmission line performance in terms of the line losses with voltage sensitive loads was studied in [3]. Three types of load, namely constant power, constant current and constant impedance were considered, individually as well as in a mixed combination.

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The enhancement of the performance of the system through the controllability of dc lines was studied in [4]. The performance was intended as the interconnected network stability with heavy power transfers.

Recently, power quality is a great demand of end-users due to the increase of the load sensitivity. Also power quality is a demand of regulatory agencies [5]. Voltage sags are the worst power quality disturbance for sensitive end-users. Therefore, it is necessary to appraise the performance of power lines in terms of their influence on voltage sags indices.

A new method to estimate power lines performance in terms of several voltage sags indices is now proposed. A set of new indices are introduced. These new indices accurately portrait the average behavior of a group of loads during voltage sags. The proposed indices are: instantaneous load variation, average load variation and non supplied energy.

A study case showing the performance of each power line and groups of lines aggregated by the class of voltage is described. The method includes the estimation of a single performance index that consolidates the set of sag indices.

III. New Performance Indices

Nowadays some electrical utilities evaluate the performance of transmission lines only based on the total number of faults registered in each line. An advance to this index is used in some situations, performing a weighted sum of the number of the different types of faults. In order to perform this weighted method, it is necessary to determine how much severe is a three-phase fault than a single-phase one or a two-phase one.

A new proposed method to estimate the performance of power lines combines a set of new voltage sags indices. These indices are related to the effect of voltage sags on sensitive end-users. Being the main contribution of the method, these indices are: instantaneous load variation, average load variation, non supplied energy.

The instantaneous load variation corresponds to the sudden reduction on the load. The average value and the duration are estimated in order to represent the load variation by a rectangular area on the chart. An example of instantaneous load variation due to a voltage sag is shown in Fig. 1.

The analysis of the load variation during voltage sags is based on the variation of the load curve with respect to the forecasted load curve. The non supplied energy (NSE) was estimated by the product of the average load reduction and the duration, according to (1).

$$NSE = \Delta P_{av} \times \Delta t \quad (1)$$

Where ΔP_{av} is the average load variation and Δt is the duration, i.e., the time until the load reaches the forecasted value.

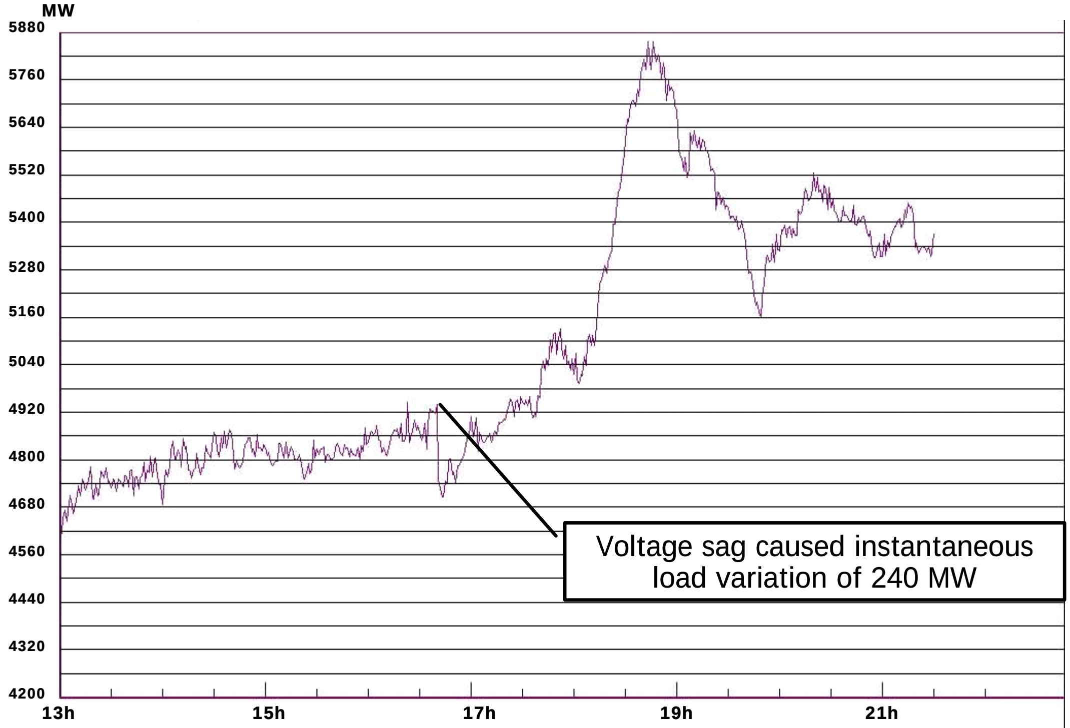

Fig. 1. Load chart showing the period when the voltage sag happens.

IV. Study Case

A. The power system

The CEMIG transmission system is composed by power lines of 138, 230, 345 and 500 kV. The transmission system is owned by the State of Minas Gerais. It is operated in agreement with the Brazilian Independent System Operator (ONS) due to the large interconnection with the main Brazilian transmission grid. The transmission system simplified diagram is shown in Fig. 2. The length of the power lines classified by voltage level is shown in Table I. Some more details about lines length and voltage level are presented in Appendix.

The CEMIG system has a meshed sub-transmission network in 138 kV. Therefore, faults in these lines are not expected to cause interruptions to end-users. Hence, the load variation shown in Fig. 1 is a consequence of voltage sags.

TABLE I
LENGTH OF THE TRANSMISSION NETWORK

Voltage	Length (km)
138 kV	5110
230 kV	1022
345 kV	2490
500 kV	2845
Total	11468

Fig. 2. Simplified single-line diagram of the power system. The location of the DFRs are indicated with stars-marks.

B. Voltage sags recorded by DFRs

All the events registered by the 64 DFRs are transmitted to the Operation Planning Department. This group is responsible for the analysis of all the disturbances and protection events in the transmission system of CEMIG.

The DFRs register the currents and voltages when voltage drops below 90 % of nominal voltage.

The files with the instantaneous voltages were supplied in Comtrade format and were processed to obtain the rms values. The rms values were obtained using a one-cycle calculation window. Each file contains 2.5 seconds of phase to neutral instantaneous voltage measurements.

Voltage sags were characterized by magnitude and duration. The sag magnitude was given by the minimum rms phase to neutral voltage. The sag duration was estimated as the period where the voltage was below 90 % of the nominal voltage in the phase that experienced the minimum voltage.

After this process, a total of 258 short-circuits were obtained during one year. Those short-circuits generated 632 voltage sags seen by the 64 DFRs. The voltage sags are represented in the magnitude / duration chart shown in Fig. 3. The chart shows that most of the sags have a magnitude above 0.70 pu and a duration below 200 ms. However, there were some very severe sags whose magnitude was below 0.50 pu and whose duration was greater than 500 ms. These severe events were expected to have great influence on the loads behavior.

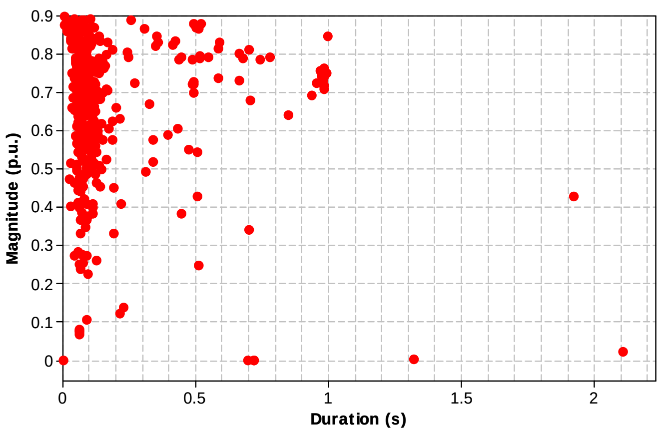

Fig. 3. Magnitude / duration chart of the sags registered by DFRs.

V. Results

In order to show how the data was collected a fault registered at the power line L9 (230 kV) is presented in Table II. The fault was three-phase, caused by lightning, with an estimated impedance of 0 ohms.

TABLE II
FAULT AT LINE L9 (230 KV)

Date dd/mm/yy	Time	Fault impedance (Ohm)	Cause	Type
29/11/04	22:05:54:045	0	Lightning.	LLL

The sags registered by the DFRs during the mentioned fault are shown in Table III. Four of the 64 DFRs triggered as a consequence of voltage sags. The deepest sags were seen at the substations IBAD and IIGU.

TABLE III
VOLTAGE SAGS REGISTERED BY THE DFRS

DFRs	kV	Mag. (p.u.)	Dur. (s)
IBAD	230	0.59	0.104
IIGU	230	0.721	0.081
IIGU	138	0.747	0.075
IIGU	161	0.755	0.079

The load experienced a significant variation as a consequence of those voltage sags, as shown in Table IV. Instantaneously 190 MW of load were lost. The load recovered the expected value after 25 minutes. During this period the average load variation was 80 MW and the non supplied energy was 33.33 MWh.

TABLE IV
LOAD VARIATION AND NON SUPPLIED ENERGY

ΔP_i (MW)	ΔP_m (MW)	Δt (min)	NSE (MWh)
190	80	25	33.33

The performance of each power line is analyzed in terms number of faults, type of fault, instantaneous load variation, average load variation, and non supplied energy. Table V shows the lines order based on the total number of faults.

TABLE V
NUMBER OF EVENTS

Power line	Faults
L35	25
L34	18
L2	15
L61	14
L39	10

Table VI presents the performance of five lines based on the weighted sum of the events according to the different types of faults. The weights were considered as follows:

- line to ground faults = 1;
- double-line to faults = 3;
- line to line to ground faults = 3;
- three phase faults = 6.

The resultant ranking changes significantly the first order. For example, line L35 is the first one based on the first index, but 24 of the 25 faults registered along it were line to ground and the last was a three phase fault. The total score of 30 was less than 32 associated to the 4 double-line to ground, 8 line to ground and 2 three phase faults of line L61.

TABLE VI
TYPES OF FAULTS

Power line	Total Score
L61	32
L35	30
L39	28
L29	26
L34	18

From Table VII forth all the results are referenced only to 37 faults that caused significant load losses, only 14% of the 258 total number of events. Table VII lists five lines with the worst performance according to the total instantaneous load variations.

TABLE VII
INSTANTANEOUS LOAD VARIATION

Power line	ΔP_i (MW)
L61	867
L42	710
L4	529
L3	520
L29	353

The lines ranking according to the total average load variation follows the prior result. Comparing Table VIII with Table VII the main difference is that line L4 rose to the first place.

TABLE VIII
AVERAGE LOAD VARIATION

Power line	ΔPav (MW)
L4	410
L61	320
L42	302
L3	196
L22	153

Considering the non-supplied energy the new lines classification is presented in Table IX. Lines L26 and L38 came out only in this last index.

TABLE IX
NON SUPPLIED ENERGY

Power line	NSE (MWh)
L42	761
L26	552
L3	434
L61	296
L38	225

It is important to remark that the results shown in these previous tables are the addition of all the events. For instance, the NSE of L42 (761 MWh) is the total result for the one-year monitoring period.

It is clear that considering only the total number of short-circuits as a decision-making factor for system upgrades is not the best decision. When observing indices that take into account the impact of each event on consumer loads the performance is very different. The tables above show that L35 has the worst performance on the total number of events. This power line also has a large score when types of faults are weighted. However, when load variations are observed, L35 doesn't appear in any of the top 5 lists. Observing all five lists, it is possible to observe that L61 is the only one that appears in all of them.

The performance of the lines considering only the events that caused significant load variation was also estimated by voltage level. The lines were aggregated in 4 classes of voltages: 138, 230, 345, and 500 kV. The results are shown in Table X. The number of events at 138 kV lines was larger than the number of events at all other voltage levels.

The other performance indices ΔP_i, ΔP_{av} and NSE are now calculated per event, i.e. the total value rated by the number of faults. The largest ΔP_i/event and ΔP_{av}/event are found for 138 kV lines. The NSE/event was the largest for 230 kV lines. However, if the number of event is considered, the total NSE caused for 138 kV lines was the largest.

TABLE X
PERFORMANCE GROUPED BY VOLTAGE LEVEL

Fault location	ΔP_i/event (MW)	ΔP_{av}/event (MW)	NSE/event (MWh)	# events
138 kV	103.2	56.4	38.8	25
230 kV	103.8	51.2	62.3	6
345 kV	64.5	38	52.2	2
500 kV	25.5	25.5	0.64	4

It is not clear which is the most relevant index to evaluate power line performances. In order to come with a single ranking a combination of the previous ones is done giving specific weights to each ranking and position as indicated in (2):

$$P = \sum_{i=1}^{5} w_i * r_i \tag{2}$$

Where P is an aggregated index that shows the performance, w_i is the weight give to each ranking and r_i is points given to the position in the ranking. For instance, the worst performance is given 5 points, the second worst is given 4 points and so on.

A ranking with the performance of the power lines shown in the Tables V-IX has been estimated using (2), were all rankings were considered with the same weight ($w_i = 1$). This is an arbitrary choice and each utility have to choose the weights according to its own convenience.

The performance considering each index and the aggregated one is shown in Fig. 4. It is important to highlight that in this analysis the highest index means the worst performance.

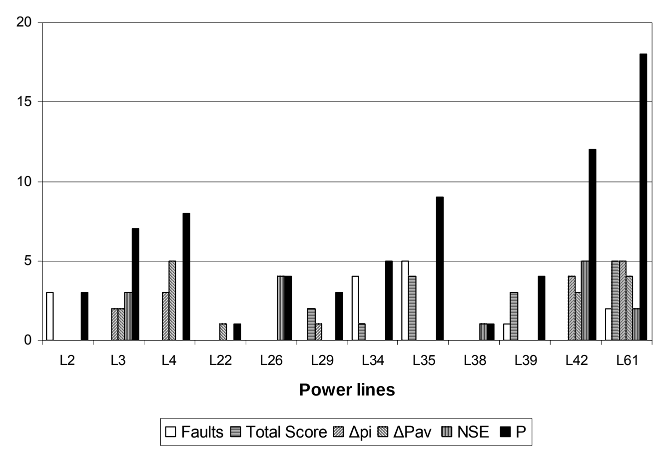

Fig. 4. Aggregated performance

Fig. 4 shows that power line L61 obtained the worst performance according to the *P* index. The second worst performance was obtained by L42. None of these power lines appeared in the ranking according to the number of faults. Therefore, the performance index that takes into account the load response to voltage sags gives new relevant information about the power line performance.

VI. CONCLUSIONS

A method to estimate power line performance in terms of a new set of voltage sags indices was proposed. The sag indices reflected the load behavior during the disturbance.

The results indicated that the usual criterion to evaluate lines performance based only on the total number of faults leads to distinct results compared with new proposed criteria. Considering the impact on end-users loads, the power lines performance rankings presents very different lines arrangement.

An aggregated performance index has been proposed. This new index gives a clear indication of which power line has the worst performance. Therefore, it indicates to the utility engineers where is more relevant to invest to upgrade the power grid.

The lines were also grouped by voltage classes. The 138 kV class presented the worst performance in terms of number of events and load variation. This is partly a consequence of the short electrical distance between the fault position and the loads.

VII. APPENDIX

Table XI shows some important data of the 69 transmission lines considered in this work.

TABLE XI
TRANSMISSION LINES DATA

line code	voltage (kV)	length (km)	line code	voltage (kV)	length (km)
L1	345	74.4	L36	138	11.93
L2	345	62.48	L37	138	74.4
L3	345	231.04	L38	138	44.68
L4	138	54.62	L39	138	55.03
L5	138	37.72	L40	138	43.4
L6	138	2.19	L41	138	71.85
L7	138	6.94	L42	500	148.56
L8	138	8.61	L43	138	17.2
L9	138	8.61	L44	138	27.6
L10	345	31.65	L45	138	21.87
L11	138	13.4	L46	500	23.92
L12	345	198	L47	500	120.31
L13	500	228.17	L48	345	53.65
L14	500	228.41	L49	138	45.99
L15	500	127.65	L50	345	66
L16	138	37.5	L51	345	181.9
L17	138	107.2	L52	345	181.95
L18	500	134.56	L53	138	37.02
L19	138	78.3	L54	138	58.67
L20	500	86.83	L55	500	248.44
L21	230	140	L56	500	96.29
L22	230	90.96	L57	500	166
L23	138	127.7	L58	230	80.25
L24	230	50.25	L59	138	45.99
L25	138	6.72	L60	138	88.12
L26	230	43.83	L61	138	141
L27	230	50.25	L62	138	36.82
L28	230	26.9	L63	138	89
L29	230	84.36	L64	138	22.11
L30	138	36.73	L65	138	8.89
L31	138	44.6	L66	138	7.46
L32	138	44.78	L67	138	7.46
L33	138	87.04	L68	345	89.2
L34	500	105.58	L69	345	50
L35	500	342.71			

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IX. Biographies

Roberto Chouhy Leborgne (M'2001) received his M.Sc. degree in electric power engineering from Itajubá Federal University, Brazil, in 2003 and his Ph.D. degree from Chalmers University of Technology, Gothenburg, Sweden, in 2007.

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