On ensuring dynamic voltage stability of critical loads in the electric power systems of industrial facilities

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Abstract. Voltage sags and interruptions in the electric power systems (internal grids) of industrial facilities are caused by various short circuits, including those that occur in external grids. If the depth and duration of such sags and interruptions exceed the rated limits for critical loads, they cause continuous processes to shut down, which produces defective products and entails substantial losses. Russian standards and regulations do not set forth requirements with respect to voltage sags and interruptions, which means that industrial companies cannot sue grid operators for damages. This is why dynamic voltage stability of critical loads involved in continuous processes has to be addressed within the internal grid. They analyze the effectiveness of solutions designed for dynamic voltage stability of critical loads; these can be shared, used on a single site or designed to power secondary circuits. It shows that use of dynamic voltage restorers (DVR) and dynamic voltage sag correctors (DVSC) can be a cost-effective solution if the topology and specifications are configured appropriately. The paper presents general technical requirements for sag and interruption compensators, which are adjusted for cost-effectiveness. Case-specific feasibility testing should be based on daily readings of electrical parameters and electric power quality readings, calculated electromechanical transients, and a feasibility study. Use of DVRs at an industrial facility helped stabilize the voltage curve and reduce the span of irregular voltage fluctuations by a factor of 3, reduce the average voltage at the 6 kV busbars without compromising equipment performance, and improve the starting conditions for AM clusters and self-starting conditions for large AMs. Thus, lowering the elevated voltage at the 6 kV busbars helped cut electricity purchase costs. In most cases where accidents cause disturbances in the external 110 kV grid, DVRs coupled with the automatic voltage controls of power transformers were able to prevent process shutdowns, which constituted the key cost effect.
1. Introduction

In Russia, electric power quality indicators (PQI) for the grid-consumer interface are rated for any operating situation of the external grid with the exception of deviation cases pertaining to random events, including [1]:

- voltage sags (below 90% of $U_{nom}$ in at least one phase);
- voltage interruptions (below 5% of $U_{nom}$ phase voltage in all phases);
- overvoltage and pulse voltage (switching and atmospheric).

Thus, each such cycle — (i) short circuit (SC), (ii) power system protections (PSP) triggered, (iii) automatic reclosers (ARC) or automatic load transfers (ALT) triggered, causing asynchronous motors (AM) to self-start — constitutes voltage sag or interruption. These cycles constitute the vast majority of short-lived voltage sags or interruptions in the internal grids of industrial facilities.

PQIs set forth in the electricity delivery contract and applicable to operator-to-facility transmission should be taken into account when:

- testing the feasibility of the grid operator’s projects regarding the external grid supplying the facility;
- calculating the facility’s damages resulting from the grid operator’s failure to meet the contracted requirements for further indemnification.

However, electricity delivery contracts do not set forth requirements regarding voltage sags and interruptions, as these indicators are not regulated by national standards. Thus, grid operators are not legally liable and are not motivated to take appropriate measures. Industrial customers are unable to get damages arising from voltage sags and interruptions.

Therefore, dynamic voltage stability of critical loads involved in continuous processes has to be addressed within the internal grid. This can be done by maintaining voltage at the busbars of critical loads when voltage sags or interruptions occur in the external grid [2-4].

This paper analyzes the effectiveness of using compensators to ensure the dynamic voltage stability of loads, where such compensators are configured on the basis of electrical parameters and PQIs (daily readings) and calculations of electromechanical transients; another objective is to draft general technical requirements on such devices.

2. Research methods

Electrical parameters and PQIs were measured by MI 2892 Power Master instruments (METREL, Slovenia) on a daily basis; readings were split into two subsamples:

- measurements taken at 6 kV busbars before implementing the new solutions;
- measurements taken at 6 kV busbars after implementing the new solutions.

Voltage and PQIs were measured in the secondary circuits of instrument transformers that measured voltage at the 6 kV busbar sections.

Electromechanical transients were calculated in MUSTANG-90 software (Russia) in two steps:

- first we calculated transients that would occur in a variety of disturbances in the external 110 kV grid without implementing the solutions;
- then we did these calculations after implementing the solutions.

3. Overview of Solutions for Internal Grids

Known solutions designed for dynamic voltage stability of the load are classified as:

- shared solutions, which are used by all or most loads of an industrial facility;
- single-site solutions, which cover a single group of critical loads connected to a single busbar section, or even each load specifically;
- solutions that power secondary circuits of power system protections, automatic controls, and other equipment.
This paper does not cover the third class; it focuses on single-site solutions, which seem most appropriate as only some critical loads do not tolerate short-term voltage sags and interruptions at all.

Use of dynamic voltage compensators (DVR) and a dynamic voltage sag corrector (DVSC), which include inverter converters of various topologies, is reasonable as they have several important advantages:
- they can inject inductive and capacitive current without need for many passive elements and switching transistor (thyristor) groups, which improves their energy density and reduces capital and maintenance costs;
- there is no need to adjust for possible voltage resonance;
- use of high-frequency pulse-width modulation where the carrier and control signals are synchronized minimizes the harmonic distortion of current and voltage curves without using passive filters;
- absence of inrush currents;
- reactive current injection does not depend on the residual voltage at the connection point (CP) [5].

Let us analyze the effectiveness of using DVRs and DVSCs in the internal grids of industrial facilities.

DVRs fall into two types: shunt-connected and series-connected; they are identical in structure but use different connections. Shunt-connected DVRs connect in parallel to the load; see Fig. 1a. Series-connected DVRs modulate the required compensatory voltage component on the primary winding of the coupling transformer, which is series-connected to the circuit of the isolated load; see Fig. 1b. The feasibility of using an energy storage system (ESS) as part of a DVR is discussed below.

![Figure 1. Simplified single-line circuit diagrams: (a) shunt-connected DVR; (b) series-connected DVR](image)

Shunt-connected DVRs are normally used to minimize the effect of load specifications and process parameters on the functioning of other critical loads. Their effectiveness with respect to the dynamic voltage stability of the load depends on the ratio of equivalent resistances on either side of the DVR connection point. In case of a high-power SC in the external grid, most of the compensatory current from the DVR will go into that grid. In that case, greater apparent power of the DVR will be required from shunt-connected DVR than that from its series-connected counterpart in order to ensure dynamic voltage stability of the load, provided that load and voltage sag parameters do not change.

Fig. 1 shows the required apparent DVR power for various values of $\cos\phi$ and short circuit ratios (SCR) for a voltage sag depth of $0.8U_{\text{nom}}$, load current $I_{\text{nom}} = 1$ p.u., and target load busbar voltage $U = 1$ p.u. ($U_{\text{nom}}$). In Fig. 2, the hodograph radius corresponds to the required apparent DVR power; the angle corresponds to $\cos\phi$. 
Hodographs are shown for inductive $\cos \phi$ (typical of industrial facilities) at different SCR values, which quantify the power output of the external grid. SCR is calculated as follows:

$$SCR = \frac{S_{SC}}{P_{DVR}}$$ (1)

where $S_{SC}$ is the power of a three-phase SC at the DVR connection point; $P_{DVR}$ is the active DVR power.

**Figure 2.** Hodographs of the apparent DVR power required to compensate a voltage sag of $0.8U_{nom}$:
(a) series-connected DVR; (b) shunt-connected DVR

Fig. 2 shows that at SCR = 8, which is usually less in the internal grids of industrial companies, a shunt-connected DVR will have to be more than three times as powerful as its series-connected counterpart. If the electrical connection to the transmission grid has high inductance, DVRs should be compared on a case-by-case basis to make the optimal choice.

Once the required apparent DVR power has been found for the target voltage sag, it is time to decide which DVR control to use: zero or minimum active power.

Minimum active power is the preferable method if the critical loads are not vulnerable to instantaneous surges in the voltage curve phase. In this case, the system will be able to maintain the required busbar voltage for the critical loads over the required time as it compensates voltage sags by injective reactive power, i.e., without connecting the ESS to the DC busbars of the DVR. Use of this principle is limited only by the voltage sag depth. Fig. 3 visualizes the zero active power method.

**Figure 3.** Visualization of the zero active power method:
(a) single-line equivalent circuit; (b) vector diagram
The inequality that defines the applicability domain follows from the vector diagram in Fig. 3b:

\[ U_{\text{grid}(Q_{\text{min})}} \geq U_{\text{load}} \cos \varphi, \]  

as well as the injection (compensation) voltage formula:

\[ U_{\text{inj}} = U_{\text{load}} \sin \varphi - \sqrt{U_{\text{grid}}^2 - (U_{\text{load}} \cos \varphi)^2} - I_{\text{load}} X_{\text{grid}}. \]  

From Eq. (3), one can plot a hodograph of the required apparent power for a series-connected DVR that uses zero active power; voltage sag for compensation equals 0.8\( U_{\text{nom}} \), inductive \( \cos \varphi \) of the protected load and the SCR vary, see Fig. 4.

**Figure 4.** Power requirement hodograph for a series-connected DVR that uses zero active power

Outside the applicability domain of this method, another method is applied: minimum active power. This method involves an ESS as part of the DVR; the ESS is controlled to minimize the discharge rate with constant voltage sag parameters.

Minimum required active ESS power is attained by maximizing the active power drawn from the external grid; the injection voltage is found by the formula:

\[ U_{\text{inj}} = \sqrt{(U_{\text{load}} \cos \varphi - U_{\text{grid}})^2} + (U_{\text{load}} \sin \varphi + I_{\text{load}} X_{\text{grid}})^2. \]  

Minimum active power as a method can be considered an extended version of zero active power. When outside the applicability domain of either method, DVR can use minimum apparent power injection, see Fig. 2 [5].

DVSCs (Fig. 5) have a different topology, as they feature a circuit through which current circulates when the switching unit is disconnected; thanks to this feature, DVSCs can be used to reliably deliver electricity to the load during ARC or ALT-related dead times. This topology can compensate voltage interruptions regardless of the equivalent resistance in the external grid [6].
Figure 5. Simplified single-line circuit diagram of a DVSC exceeding 500 kVA in capacity

According to Russia’s distribution grid statistics, the characteristic (average) voltage sags range from 35% to 99% and last 1.5 to 3 seconds, and up to 30 or more sags occur per annum. In 110-220 kV grids, sags usually occur due to single-phase SCs in overhead power lines, which account for 70% of all cases (20% attributable to two-phase SCs and 10% - to three-phase SCs) [7].

Voltage sag and interruption parameters largely depend on the PSP algorithms and configurations in the internal and external grid as well as on the switching units’ opening times. Therefore, upgrading DVSCs to shorten SC elimination times can effectively minimize their characteristics [8, 9].

Based on the above, DVRs and DVSCs are generally required to:

- keep busbar voltage for critical loads within the required range during voltage sags and interruptions (limits on depth and duration application);
- perform as required while using minimum ESS power and energy density, if any;
- minimize active power loss in inverter converters and coupling transformers (if any) in normal operation (no SCs, no ARC or ALT-related dead times);
- have minimum effect on the voltage/current harmonics and $\cos \phi$ at the connection point;
- maximize the specific apparent power (kVA/kg, kVA/m³) and energy density for as much as the design allows;
- be scalable, i.e., allow connecting additional ESS modules.

DVR (DVSC) topology and specifications should be configured on a case-by-case basis when designing the internal grid of an industrial facility as part of a new construction or reconstruction project. In case of reconstruction, design should be based on daily readings of electrical parameters and PQIs. This helps optimize DVRs (DVSCs) for cost-effectiveness.

Otherwise, use of either technology is only cost-effective if the production line is extremely demanding to electricity delivery, and even a short outage will compromise the bottom line. Below is a real-world industrial case of using DVRs [10].

4. Results
Several issues had been plaguing the internal grid of an industrial facility for many years:

- an AM cluster couldn’t start directly without pooling 6 kV busbar sections for a short parallel run, which entailed the risk of complete blackout of all critical loads if an accident causes disturbance;
- an AMs cluster (critical loads simultaneously involved in the process) with per-unit power of 1 MW or less, or two large AMs with per-unit power of 4.4 MW (one per 6 kV busbar section) wouldn’t self-start;
- 6 kV busbars had to run at higher voltage (up to 6.6 kV) to directly start some AMs.

Due to these issues, SCs in the external 110 kV grid were very likely to cause a shutdown in the continuous process. Last three years averaged at 24 shutdowns per annum or twice a month. Zero active power DVRs were feasibility-tested as a solution.

Electromechanical transients were calculated in order to find the minimum DVR power requirement
for direct starting of AM clusters or self-starting of large AMs with an appropriate post-ARC or post-ALT delay.

With the calculations at hand, it was decided to install two DVRs, 10 MVA each, and connect them to the 6 kV busbar sections. To connect the DVR to a 6 kV supply line, we used two 10 MVA, 6/0.69 kV step-up transformers and two 6 kV cells at the substation. The DVR eliminated the need to pool 6 kV busbar sections into parallel operation, which also improved the reliability of internal power circuitry. Fig. 6 shows a simplified single-line circuit of the industrial facility with two DVRs.

Fig. 7 shows the original daily voltage curve of the 6 kV busbars of the facility; the trajectory is wavelike due to the specifics of the production process, and the daily average voltage is 6.6 kV.

![Figure 6. Simplified single-line circuit diagram of the industrial facility with two installed DVRs](image1)

![Figure 7. Original daily voltage curve of the 6 kV busbars of the facility](image2)

Voltage curve smoothed out the automatic voltage control system (AVC) to issue control actions to voltage controls when 110/6 kV power transformers (T-1, T-2, T-3) are loaded, see Fig. 8.
Figure 8. Daily voltage curve of the 6 kV busbars with power transformer AVC in place

We were further able to stabilize the voltage curve by using DVR, which reduced the span of irregular voltage fluctuations by a factor of 3, see Fig. 9.

Figure 9. Shortened voltage fluctuation span due to DVR

Fig. 9 leads to a conclusion that using DVRs helped reduce the average voltage at the 6 kV busbars by 0.4 kV to 6.2 kV without compromising equipment performance, which also improved the conditions for starting large AMs. Thus, lowering the elevated voltage at the 6 kV busbars helped cut the facility’s electricity purchase costs.

In most cases where accidents caused disturbances in the external 110 kV grid, DVRs coupled AVCs were able to prevent process shutdowns, which constituted the key cost effect.

If the excitation voltage of the generator sets (GS) at the mini-CHP is relatively low, then in pre-emergency operation, the reactive power of the load ($Q_{\text{load}}$) is mainly covered by the external grid [11-13]. Should the internal grid become islanded, a voltage sag will occur due to substantial active power deficit (total power draw $P_{\text{load}} = 70$ MW, total power output of the generator sets at the CHP $P_{\text{GS}} = 20$ MW). Voltage sag will be the deeper, the lower the GS voltage is. At a GS voltage of $0.95U_{\text{nom}}$ AM slip ($s$) will increase, the voltage will decrease, and a voltage collapse will occur, see Fig. 10a. In this case, load is shed, first, due to undervoltage, then – due to voltage collapse that takes less than 0.1 s to occur. As a result, the continuous process sustains a power outage, the internal grid’s frequency rises to 54 Hz briefly, and the steady-state value sets at 51.5 Hz.
Figure 10. Transients (a) $Q_{\text{load}}$ in pre-emergency operation covered by the external grid; (b) $Q_{\text{load}}$ in pre-emergency operation covered by the generator sets of the mini-CHP

If in pre-emergency operation, the generator sets of the mini-CHP can cover nearly the entire reactive power of the load ($Q_{\text{load}}$), islanding will only cause a minimum undervoltage in the internal grid (up to 4%), the load will retain voltage stability. The resulting active power deficit will cause a reduction in frequency, see Fig. 10b.

If upon islanding, the 110 kV external grid sustains a three-phase SC near the busbars of the 110/6 kV substation, AMs destabilize quickly, voltage drops, substantial load-shedding occurs, and frequency rises. Fig. 11a shows two transients in superimposition for comparison.

Figure 11. Transients in case of a three-phase SC in the 110 kV grid (a) islanding without SC (bold lines) and with a 0.2 s SC (normal lines); (b) with a fast-response load-shedding

Since significant undervoltage, load-shedding, and a disruption of the continuous process occur in all cases of islanding the internal grid, there is a need for fast-response load-shedding triggered by islanding [14, 15].

Transients were calculated for a load-shedding equal to active power deficit as of 0.3 s after the onset of the SC (0.1 after the elimination thereof). Fig. 11b shows that all AMs in the internal grid self-restart successfully where fast-response load-shedding is in place.
Adopting multiple automatic voltage controls and systems at a single facility requires coordination of their algorithms. Otherwise, local AVCs of the power transformers and AVCs of DVRs and automatic generator excitation controllers at the mini-CHP may conflict, i.e., issue incompatible or inconsistent control actions.

5. Conclusions
The results obtained allow us to draw the following conclusions:
1. In the current state of the art, dynamic voltage stability of critical loads involved in continuous processes has to be addressed within the internal grid.
2. Use of dynamic voltage restorers (DVR) and dynamic voltage sag correctors (DVSC) effectively compensates for voltage sags and interruptions caused by short circuits in external grids and in ARC/ALT cycles. These solutions can be cost-effective if their topology and specifications are configured well, and power outage of critical loads is prohibitively costly.
3. In the context of the cost-effectiveness of such devices, general requirements on the voltage sag and interruptions compensators as presented herein could be of use as part of the design guidelines regarding the configuration of compensation systems.
4. Their parameters should be configured on the basis of electrical parameters and electric power quality indicators (daily readings) coupled with calculations of electromechanical transients.
5. Relatively low excitation of the generator sets at the internal grid’s mini-CHP would be unacceptable as islanding in such case would cause significant undervoltage, an increase in AM slip, and a voltage collapse resulting in a shutdown of the continuous process.
6. The internal grid should be islanded due to an SC: AMs destabilize quickly voltage drops, and substantial power shedding occurs site-wide, whereas the frequency increases. In this case, fast-response post-islanding load-shedding could effectively prevent a voltage collapse.

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