COLUMN

Transformer energisation after network blackout

Impact on network restoration and improvement of its process

ABSTRACT

According to ENTSO-E Network policy 5, responsibility for system restoration after a blackout is on the shoulders of Transmission System Operators (TSOs). They are advised to have a firm plan in place for regular testing of system restoration functionality. Part of the network restoration includes energising transformers to supply various underlying grids. However, transformer energisation after a blackout is complex and there is a significant risk for network restoration to fail because the network is quite weak in the first phase of the process and due to specific transformer behaviour.

This paper will focus on relevant items in regard to energising transformers and an alternative robust 'soft-energisation' methodology to supply transformers simultaneously after a network blackout. A qualitative assessment is made for the 'classical' and 'soft-energisation' methodology for network restoration purposes. Also, feasibility studies are elaborated.

1. Introduction

A robust and fast network restoration process after a blackout is a key element for TSOs, in order to restore power as quickly, reliably and safely as possible, while minimising the stress on network components. This last condition is vital as too much electrical stress, e.g. transient voltages or currents, could trigger component failure or protection relays. Trips of network components during the restoration process are undesirable and might cause another blackout, extending the damage for consumers. Dealing with voltage oscillations is one of the technical challenges that a TSO has to deal with for network restoration purposes.

Soft-energisation is a sophisticated method to re-energise a network after a blackout: it mitigates the risks caused by transient phenomena without having to rely on an extensive analysi s

For network restoration after a blackout, there are two main methodologies that can be applied to energise network comoponents: the 'classical' and the 'soft-energisation' methodology. In this contribution, the focus is on these methodologies and not on the start of the involved black start generator that has to act as a voltage source.

2. Network restoration: 'Classical' and 'soft-energisation' methodology

2.1. Classical methodology

For the 'classical' network restoration methodology, a dedicated black start generator must be started and accelerated via a black start facility. In Western Europe, a gas turbine is typically used as a black start generator. The black start facility usually comprises (emergency) diesel generators and/or a small gas turbine to accelerate the black start generator and to supply its auxiliaries. As soon as the black start generator is running at full speed at no load and its voltage regulator is excited, the unit can supply a transmission substation, overhead lines, cables and transformers.

If the black start generator supplies a main substation, the voltage supply can be switched to a transformer by closing the circuit breaker involved. Due to this switching, the transformer gets into saturation because transformer flux can increase beyond its rated value, seeking for a high inrush current (since the transformer magnetizing reactance decreases significantly during saturation). During this switching, the black start generator has difficulties to maintain substation voltage because the network is quite weak (low fault level) if only the black start generator is in operation. As a result of this, switching transient voltage oscillations occur which will have even higher peak values if there is a cable between the mentioned circuit breaker and the transformer.

The transient voltages cause severe electrical stress on network components, which can lead to damage and further network component trips and cause system restoration to fail. This classical methodology requires detailed transient simulation studies in order to assess voltage oscillations, for which it is crucial to have specific criteria for transient voltages and data about transformer's magnetizing behaviour.

2.2. Soft-energisation methodology

To reduce the risk of transient voltage oscillations and triggering follow-up blackouts, network restoration can be applied according to the principle of soft-energisation. In this methodology, all involved non-energised network components (overhead lines, cables and transformers)

A robust and fast network restoration process after a blackout is a key element for TSOs in order to restore power as quickly, reliably and safely as possible

are first connected to each other via their substations (a so-called dead bus bar network configuration) and the running black start generator without activated voltage excitation.

Once the network section is thus prepared, the generator terminal voltage at the black start generator is slowly increased from zero to the rated value. This voltage ramp-up is carefully controlled in order to slowly increase transformer flux to its rated value, so that transformer saturation and inrush currents are prevented. As a result, all network components are energised gradually and simultaneously without any transient oscillation, reducing the stress on network components and substation assets.

Considering that during the energisation process transformers are controlled within their range of linear operation, i.e. a transformer only needs a small no-load current for magnetisation, even a small black start generator is capable of energising a rather large amount of transformers simultaneously. This implies that in a certain region more power plants could be fit for network restoration and not only the large power plants.

3. Impact of transformer residual flux

Transformer residual flux is one of the most important topics to consider for a network restoration process and is briefly discussed in this chapter. It is strongly recommended to mitigate transformer residual flux for any network restoration process.

If a transformer is switched off, it will most likely have a certain level of residual flux:

Transformer energisation after a blackout is complex and there is a significant risk for network restoration to fail

the remaining flux in the transformer core due to the fact that the transformer's voltage and flux have a 90-degree steady state phase angle difference. The residual flux has a stochastic character and acts as a kind of offset that may get the transformer into deeper saturation during its next energisation. Consequently, it is more difficult for the black start generator (low fault level) to control voltages during network restoration and transient voltage oscillations are more severe.

It is remarked that during normal network operation (no blackout and normal generation dispatch) the network fault level is high, i.e. voltages can be maintained by all running generators and consequently transient voltage oscillations are prevented.

4. Network restoration feasibility study

For any network restoration process it is especially important to study the involved transformer energisation because if it fails, the restoration process is hindered and customers are not supplied for a longer period of time. It is needed to perform a steady state (load flow) study to assess network voltages and especially reactive power flows that must be handled by the black start generator's capability. For the classical network restoration methodology, a transient study must also be carried out, which is not needed for the soft-energisation methodology.

Relevant items for feasibility studies are elaborated in this chapter for both the classical and soft-energisation methodology.

4.1 Feasibility study: Classical method

The severe transient electrical stress that occurs when using the classical methodology can lead to damage and further network component trips, which can cause the network supply to shut down again and system restoration to fail. Detailed transient simulation studies are needed to assess voltage oscillations, for which the following is needed:

1. Transient simulation network model, in which the black start generator's automatic voltage controller (AVR) must be incorporated.
2. Individual transformer magnetizing curves, normally part of a transformer test report. A transformer's deep saturation range (≥130 % rated voltage) must be considered, which is normally not registered during its factory acceptance test (FAT). As a work-around for the missing deep saturation range one could apply a very low magnetizing reactance.
3. Assessment of the impact of transformer residual flux, including a sensitivity analysis because the level of residual flux is unknown beforehand (residual flux has a stochastic character). Literature recommends to apply a general residual flux of 70 % of the rated flux.
4. Voltage criteria for switching transients and short-time overvoltage. In general these criteria are not part of equipment datasheets and need to be determined separately via international standards and manufacturers guidelines.
5. Algorithms that determine the worst-case switching instants specially for transformer energisation, for both line- and phase voltages.

4.2 Feasibility study: Soft-energisation method

The soft-energisation approach can be used to energise any network with limited feasibility studies beforehand. Because the soft-energisation methodology causes no transient/oscillation phenomena, complex transient studies and impact assessment are not required. A major benefit is that detailed information about transformer magnetization is not needed.

Basically, only a steady state (load flow) study is needed for the soft-energisation methodology in order to assess substation voltages, reactive power flows (due to the unloaded overhead lines and cables) and the black start generator's reactive power capability.

5. Case: soft-energisation as network restoration methodology for 220/380 kV grids in the Netherlands

Since 2014, DNV GL has been involved in various network restoration studies for the Dutch transmission system operator (TSO) TenneT. TenneT, ENGIE, the owner of a black start generator, and DNV GL worked closely together in a technical feasibility study to apply soft-energisation in the northern part of the Netherlands. Live tests, energisation of 220/380 kV, 220/10 kV and generator step-up transformers were essential parts of the project. A main overview of the involved network section is shown in Figure 1.

Several factors added to the complexity of the network restoration project:

1. Energisation of 72 km (45 miles) of unloaded 220 kV overhead line (OHL)
2. Reactive power of the unloaded 220 kV lines and 220 kV cables to be handled by a shunt reactor and the black start generator
3. Saturation of unloaded transformers, with a total power of 2000 MVA
4. Transformer residual flux
5. Limited reactive and short-circuit power of the 50 MVA gas turbine generator that must energise the network section
6. Additional power plant to be started at the end of the 72 km (45 miles) 220 kV overhead line

Detailed computer simulations and live tests in TenneT's 220/380 kV grid showed that soft-energisation can be successfully applied. During this project, a mitigation measure was also developed to further reduce the risk of a generator trip or any other network component. The mitigation measure demagnetises transformers connected with the network section via the excitation control of the black start generator. After the demagnetisation, the network section must be slowly and gradually energized to the rated voltage level.

Through various tests in TenneT's 220/380 kV network, the soft-energisation methodology was verified. During these tests, the demagnetization measure was applied successfully and proven to be effective for the network restoration process of the high-voltage network. The measured impact on the 50 MVA black start generator with or without the transformer demagnetisation mitigation measure is shown in Figures 2 and 3.

Transformer residual flux is one of the most important topics to consider for a network restoration process

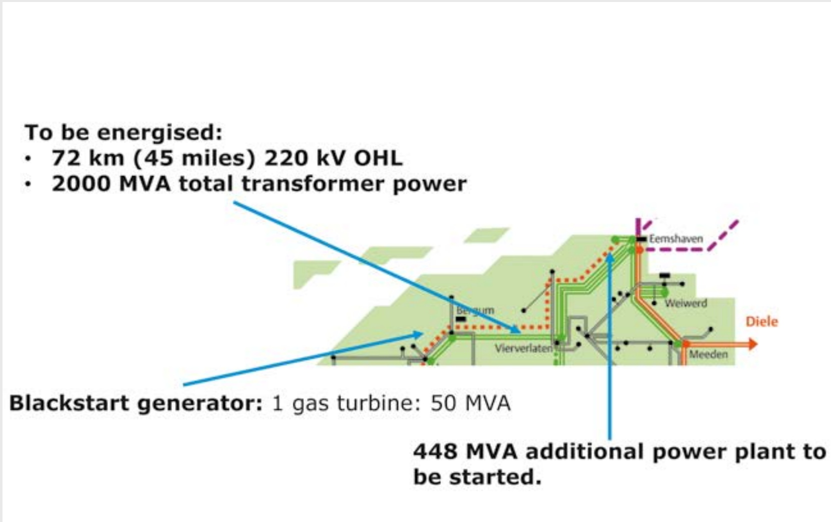

Figure 1. Overview of the network section to be energised via soft-energisation

The soft-energisation approach can be used to energise any network with limited feasibility studies beforehand because it causes no transient phenomena, but transformer demagnetisation is strongly recommended

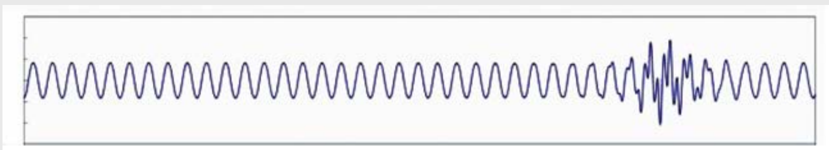

Figure 2. Without mitigation measure during live test: measured current of 50 MVA black start generator gets distorted with a transient phenomenon, indicating a risk of generator trip and hence a failure of the network restoration process

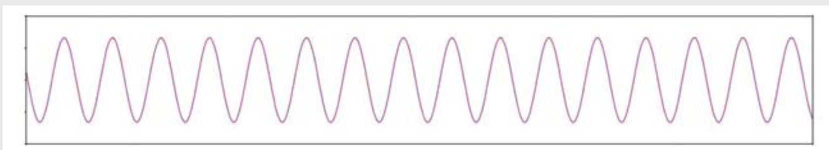

Figure 3. With mitigation measure during live test: measured current of 50 MVA black start generator is not distorted and there is no transient phenomenon, which indicates successful network restoration process

5.1 Impact of developed mitigation measure

The soft-energisation methodology is now the official concept for the energisation of the 220/380 kV grid in the northern part of the Netherlands and is tested on a yearly basis.

Concluding remarks

In this paper the complexity of transformer energisation during network restoration after a blackout has been elaborated. Because of specific transformer behaviour at the instant of energisation, and due to a weak grid during network restoration, severe transient overvoltages can occur. To assess transient overvoltages, detailed and time-consuming simulation studies must be carried out. These studies require data collection about deep transformer saturation and transient overvoltage criteria, which are quite complex to collect. A crucial part of the transient studies is transformer residual flux, which causes even worse transient voltages, being a serious risk for network restoration.

Soft-energisation is a sophisticated methodology to energise a network after a blackout, for which transformer demagnetization is strongly recommended. With this approach, network components are energized up to the rated voltage level, without any transient phenomena. Because of this, feasibility studies can be limited to steady state analysis, i.e. detailed information about transformer magnetization behaviour is not needed. For this methodology, smaller generators could be applied, i.e. the flexibility to deploy black start power increases. However, the reactive power capability of smaller generators is more strict and needs to be considered.

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