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Techno-economic impacts of automatic undervoltage load shedding under emergency

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ABSTRACT

Different schemes for voltage control under emergency are adopted in different jurisdictions around the world. While some features, such as Automatic Voltage Regulation (AVR), are common in all countries, for what concerns undervoltage load shedding (UVLS), to contrast voltage instability or collapse, different schemes are adopted. Most US transmission system operators (TSOs) adopt automatic UVLS schemes, with different capabilities and settings while TSOs in EU usually do not implement automatic UVLS but leave the decisions to the control room operators. The two options may lead to different impacts in terms of trajectory and final status of the transmission grid under emergency, with different unserved energy. In this paper we analyze the impacts from a technical and economic perspective, modeling the grid behavior with different UVLS schemes (none, manual and automatic). The comparison between the different schemes is done resorting to the Incident Response System (IRS), a software tool developed by the authors in the EU-FP7 SESAME project. An illustrative example to a realistic test case is presented and discussed. This paper shows that automatic UVLS is superior to Manual UVLS, from both technical and economic point of view, due to the fast evolution of voltage collapse phenomena and insufficient time for system operators' manual reaction. The benefits of the scheme involving the automatic UVLS can be then compared with the investment costs of equipping the network with those devices.

1. Introduction

From historic blackouts [1–3], one can observe that the main factor of most of recent system disturbances is voltage collapse, rather than the underfrequency conditions, which were prevalent in the blackouts of the 1960 and 1970s. In some power grids, such as the ones in North America, most of generation sources are located remotely from load centers and there is reluctance to allow building new generation plants in urban areas. This increases the power system dependency on the transmission network and, in case of transmission lines trip, there may be a lack of reactive power in local areas. Therefore, in these transmission systems, the protection against voltage collapse is crucial.

In the operation of power systems, when several failures happen simultaneously, commonly used protection relays (low voltage, over current) may not be able to distinguish between the voltage/current violations caused by widespread cascading failures from those caused by a local fault. This would result in more generators or lines being tripped, spreading the blackout area. So dedicated strategies for undervoltage protection are needed to avoid large scale cascading failures.

An analysis performed on blackouts happened in Europe in the past 35 years [20] clearly shows that most of them were characterized by low voltage or voltage collapse, during the cascading failure, that eventually led to power outage (Table 1).

It appears that frequency and gravity of blackout events are increasing in recent years and, due to interdependency of other infrastructures with power system, the blackout impacts on other infrastructures and society are growing. One type of system instability which can occur when the system is heavily loaded is voltage collapse [21]. Other reasons for voltage instability and collapse can be the dynamics of tap-changing transformers [22], as these components can aggravate rapid voltage decay [23,24], the presence of

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Table 1
Blackouts involving undervoltage in EU.

Country and area	Date	Main references
France—eastern part of the country	19/12/1978	[4]
France—western part of the country	12/01/1987	[4]
France–western part of the country	26/12/1999	[5–7]
UK—London southern area	28/08/2003	[8]
Croatia (southern part of the country) and Bosnia Herzegovina	12/01/2003	[9–11]
Sweden southern part of the country) and Denmark (eastern part of the country)	23/09/2003	[12–14]
Italy—all the country except for Sardinia	28/09/2003	[15,16]
Norway—Bergen, larger part of Horland and northern parts of Rogaland	13/02/2004	[12,17,18]
Greece—Athens area	12/07/2004	[12]
Poland	26/06/2006	[19]

a high percentage of loads constituted by induction motors [25], and the presence of small noise in load demand [26].

These concerns bring the necessity of reinforcing electrical infrastructures against undervoltage incidents and investing on new protection schemes to prevent huge negative impacts.

Suitable strategies for prevention of voltage collapse are required in order to save costs and mitigate socioeconomic impacts. From the structural point of view, the most effective improvement of voltage stability limits is building new transmission lines and increasing generation. But it is very difficult and expensive to find a new corridor for a transmission line or a new location for power plants, since the acceptance of new infrastructures by the population is everyday decreasing. Therefore, new solutions are being investigated to prevent larger blackouts in a more acceptable and economic way. When searching for schemes to enhance power system voltage stability, the evolution of adverse events needs to be analyzed [24].

In today's transmission systems the problem of reactive power reserve is growing because of the restructuring of the power systems involving electricity markets [27]. The voltage and reactive power control are now partially ancillary services that need to be provided by the producers (in contrast with their economic objectives) to system operators [28]. In this framework most of the TSOs are finding it difficult to meet regulatory standards and criteria without using automatic transmission controls such as reactive switching, remedial action scheme (RAS) [29], and undervoltage load shedding (UVLS). Among these control actions, UVLS is becoming more advantageous, being reliable and cost-effective in preventing voltage collapse [30].

UVLS is widely used in the US while in EU the ENTSO-E recommends to implement it within DSOs grids, but up to now it is not widespread [31]. In order to guide system operators to make decisions on when and where to allocate undervoltage protection systems, a cost–benefit based supporting tool is needed. We resort to a cascading failure simulation tool, named Incident Response Systems (IRS) [32], to capture the sequence of events during an emergency, leading to a voltage collapse. We model the power system behavior with different voltage based load shedding schemes (no undervoltage load shedding, manual and automatic) analyzing the impacts from a technical and economic perspective.

In the next section, voltage control strategies under emergency are briefly discussed, mainly focusing on different load shedding schemes as countermeasure. In Section 3, IRS will be introduced, highlighting the undervoltage load shedding model. Section 4 illustrates a comparison among the different impacts of different types of undervoltage load shedding with reference to the Austrian grid.

2. Voltage control under emergency

Voltage collapse in a power system indicates that the operation is beyond its capability for the existing conditions and contingencies. The main symptoms of voltage collapse are low voltage profiles, heavy reactive power flows, insufficient local reactive support, and heavily loaded systems. The consequences of voltage collapse often require long system restoration, which causes a huge amount of unserved energy to large groups of customers. The symptoms can be exploited by protective schemes to mitigate the collapse.

According to IEEE/CIGRE Joint TF report, "Definition and Classification of Power System Stability", the time frame for voltage stability problems varies from a few seconds to tens of minutes [33]. Voltage collapses in the long time frames are attracting much of the attention and recent investigations. These types of collapses usually occur because of loss of significant sources or loss of heavily loaded transmission capability. Simulation tools to study time dependent system response in longer time frames have only been relatively recently developed, while tools for transient analysis of power systems are very mature and widely used [34].

As one of the causes of voltage collapse is an excess of load for the given transmission system, load shedding is an effective measure and its application is increasing in large-scale power systems.

NERC's Operating Policy 6—Operations Planning [35] includes the following criteria in Section C—Automatic Load Shedding: "After taking all other remedial steps, a system or control area whose integrity is in jeopardy due to insufficient generation or transmission capacity shall shed customer load rather than risk an uncontrolled failure of components or the interconnection".

Most of power system cascading failures include low or very low voltage conditions. Voltage collapse can occur over a wide variety of time frames [34]. The voltage variation rate affects the types of countermeasures that can be put in place and it depends on time and voltage varying characteristics of the system elements like loads, automatic tap changing transformers, generator excitation controls, governor and turbine responses, protective relays, and other automatic or manual control actions.

Although several studies show that undervoltage load shedding is a very effective countermeasure in preventing voltage collapse, it may not be beneficial to all systems. For example, in systems with fast voltage decay, direct full load shedding is the only solution to prevent a larger scale blackout in the system.

Load can be shed either manually or automatically depending on the rate of voltage drop. If the time frame of the voltage drop is in the range of minutes, manual load shedding can be implemented in order to stabilize the system, the operator intervention may in fact be expected after some minutes. If, vice versa, voltage drop is faster, manual load shedding would be too slow to act timely.

2.1. Manual load shedding

In the case of manual load shedding, the TSO's operators should have preplanned guidelines and procedures to follow. Blocks of sheddable loads should be predefined and preprogrammed on the control system SCADA. The major disadvantage of manual load shedding is the burden that is placed on system operators, that have to quickly recognize arising voltage stability problems [34].

2.2. Automatic load shedding

If the voltage perturbation is caused by a single major event on the network, voltage drop is fast and manual load shedding cannot prevent voltage collapse. In this case undervoltage relays may be used to trigger automatic load shedding. There are two basic types of automatic UVLS schemes: decentralized and centralized.