Future Operational Regimes of Bulk Power Generation in The Era of Global Energy Transition: Grid Codes, Challenges and Open Issues

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Abstract—This paper explores the effects of the ongoing energy transition on the classical bulk power generation. The rapid increase in renewable penetration changes the role of grid-connected generators significantly. Large machines have been historically operated in a continuous load condition (S1) and designed based on old grid codes. In the future, flexible operational schemes and intermittent load cycling will be required. This may cause the generation system to operate far from the nominal operating condition it was designed. In parallel, new harmonized grid guidelines are being introduced. As a result of the ongoing changes, new design issues are introduced to cope with these requirements. An in-depth case study is presented. Finally, this contribution offers a view on future perspectives and open issues.

Index Terms—Load cycles, intermittent operation, Reactive capability, short-circuit capability.

Fig. 1. Different reference frames from reactive power capability.

I. INTRODUCTION

The global mix of power generation is continuously evolving as a result of worldwide decarbonization. Traditional bulk power generation was historically designed with high short-circuit power capabilities. As a result, conventional protection schemes are based on the detection of high currents. With a grid being dominated more and more by electronic power converters, the short-circuit currents decrease significantly. In general, the current from the inverters is usually not above 1.5 times the nominal rated current of the supply [1].

Another issue arises from photovoltaic production when considering the unpredictable and sudden power variations. The system must respond accordingly with high power ramping accumulated from sufficient operational reserves. This is a demanding challenge, especially if addressed by the conventional bulk power generation. The so-called "Duck Curve" depicts the effect of how the peak demand interplays with the rapid decrease of power from intermittent sources. The bulk power generation is intensified to deliver the instantaneous power difference.

The bulk power generation may soon operate in regimes that were not considered when the generators were initially designed in the past [2]. It is, therefore, important to ensure that the equipment will not be damaged and that it is compliant to the new grid code. From a historical lesson, one had to come up with the rules for each project. However, the modern grid codes try to harmonize the design procedures and standards
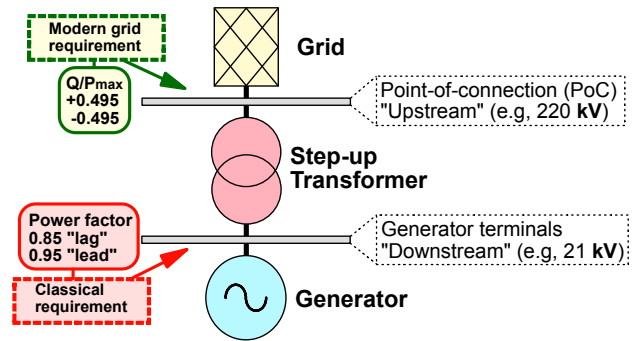
[3]. In Europe, the ENTSO-E (European Network of Transmission System Operators for Electricity) is the authorized entity, whereas, in North America, NERC (North American Electric Reliability Corporation) develops the standards. In practice, the design of the generators is guided by the IEEE standard C50.13 [4] and the IEC standard 60034 [5]. Nowadays, a new product line of generators [6] have been argued. In addition, different types of synchronous machines for various applications employ very different excitation systems [7]. The grid codes for different machines and types of systems do also vary [8].

This paper serves as a supplementary to the recent IEEE PES Technical report [9]. Moreover, this contribution provides an in-depth analysis of a case study of the new stringent capability requirements for large power generation. The impact of the increased reactive power variability is also critically discussed. It is argued that the mode of operation and active power output should also be considered when evaluating the impact of more renewable penetration into the future power grid.

The paper is organized with the following structure; The capability requirements of bulk power generation are dealt with in Section II. Then, Section III present a worked example, considering the new requirements. The section also raises some dynamic issues. Finally, Sections V and VI discusses the future load cycles of synchronous machines and concludes the paper.

II. CAPABILITY REQUIREMENTS

This section presents the capability requirements of bulk power generation in the stationary domain.

A. Short Circuit Capability (SCC)

The short circuit capability of a power system is strongly coupled to the short circuit properties of its power generation, as well as the grid topology. The ongoing changes in the mix of power generation will inevitably have an effect on this issue (i.e., more power electronics based generation).

The short-circuit ratio (SCR) of a generator refers to its ability to deliver a short circuit current under a fault at its terminals. It is generally perceived that the SCR improve the grid stability. However, it is observed to have a marginal performance improvement between 0.5 and 0.45 when using fast high-gain excitation systems [9]. Some would argue that if system studies can show no significant benefit in terms of grid stability with a unit having incrementally higher SCR, the grid codes should be more flexible. Moreover, the grid code requirements for countries with similar grid topology and standards should be harmonized. In some grid topologies, there are long distances between the bulk production (i.e., hydropower facilities) and the main consumption, which requires a higher SCR. As a result, the SCR of some generators could be as high as 0.9. It may also be relevant to reduce the SCR requirements in the grid codes for very large generators that are strategically located. For instance, the SCR of a 1600 MVA generator of thermal power plant could be as low as 0.4 [9]. For hydrogenerators, there are many poles and restrictions in the minimum air gap length, which cause a naturally higher SCR than for thermal generators.

1) Short Circuit Capability Definitions: The SCR is the inverse of the normalized (per unit) direct axis reactance (unsaturated), given by

$$SCR = \frac{I_{f0}}{I_{fk}} \approx \frac{1}{x_d}, \tag{1}$$

where the base impedance is related to the base voltage and apparent power according to $Z_b = \frac{U_b^2}{S_b}$. It can be generally shown that the SCR is directly proportional to the base power of the generator (if physical reactance X_d is constant), yielding

$$SCR \approx \underbrace{\frac{1}{X_d/Z_b}}_{x_d} = \frac{1}{X_d} \cdot \frac{1}{S_b} \cdot U_b^2. \tag{2}$$

The following values are usually considered [9]:

- IEC 60034-3 / IEEE C50.13 specifies a minimum SCR of 0.35.
- Most generators have a SCR above 0.45.
- Most grid codes require above or equal to 0.5.

SCR increases the generator size and reduces efficiency. An over-sized machine yields a significant cost impact. In addition to the nominal SCR, a dynamic SCR might be important in the cases where short-term reactive capabilities of the machine are utilized with more advanced control schemes [10].

2) SCR Design Challenges: If the machine is re-specified, it follows from eq. (2) that the power output reduces with about the same percentage as the SCR increases. From 0.45 to 0.5, the MVA goes from 1 pu to 0.9 pu. As a result, derating of the power plant is an alternative when the SCR is not sufficient for existing apparatus.

Other size considerations may involve that [9]:

- The generator weight increases with about 60 percent for a 100 percent increase in SCR, i.e., SCR from 0.45 to 0.5 yields a weight increase from 100 percent to 107 percent.
- Increasing the air gap, a 100 percent SCR increase results in 35 percent weight increase. In fact, the rated field current increases with the air gap and leads to higher temperature and lower efficiency, or a larger machine.

B. Reactive Power Capability (RPC)

The reactive power capability (RPC) is interconnected with the SCC issue. In fact, a higher SCR enhances the RPC significantly, because a smaller x_d reduces the internal parasitic reactive power consumption of the generator. The RPC has different definitions depending on the local grid codes. Historically, the synchronous generator was specified at the rated over-excitation condition, with maximum active (MW) and reactive power (MVAr). The capabilities were referred to the generator terminals. Standards like IEEE C50.13 and IEC 60034-3, defines MVAr capability at the generator terminals, 0.8, 0.85 and 0.9 overexcited power factor. The lower the power factor, the larger the machine will be. In addition, it is recommended that the generator also is capable of operating at 0.95 under-excited at rated MW.

Fig. 1 depicts how the grid codes can define the capability, either at the generator terminals or at the grid connection at the HV side of the generator step-up transformer. The requirement can specify the reactive power as a power factor or as a ratio between reactive power and the maximum active power.

EU network code makes the capability dependent on both generator and step-up transformer design [11]. In order to address this issue, on-load tap-changing (OLTC) transformers might be needed to avoid over-sizing of the generator (i.e., cost issue). It is argued that modern grid codes also should define the requirements at the generator terminals. Moreover, realistic guidelines from the transmission system operator (TSO) for the leading power factor during high system voltages and maximum lagging power factor during low system voltages is also needed.

1) Reactive Power Definitions: The reactive capability is normalised with the nominal output power (P) in the new ENTSO-E grid code. It can be calculated as a function of the power factor (P/S), where

$$\frac{Q_{max}}{P} = \frac{\sqrt{1 - \left(\frac{P}{S}\right)^2}}{\left(\frac{P}{S}\right)}. \tag{3}$$

The power factor can be calculated as with respect to the reactive capability as well, yielding

$$\underbrace{\left(\frac{P}{S}\right)}_{\cos(\varphi)} = \frac{1}{\sqrt{\left(\frac{Q_{max}}{P}\right)^2 + 1}}. \tag{4}$$

As seen in eqs. (3) and (4), the maximum reactive capability is inversely proportional to the over-excited power factor. In order to express the reactive power envelope at the connection point to the grid (upstream after the step-up transformer) [11], additional calculations are needed. The per unit generator voltage (u_t) and the generator maximum reactive power (Q_{max}) can be corrected by the following modified two-port equations:

$$\left(\frac{P}{S}\right)^2 + \left[\frac{Q_g}{S} + \frac{u_g^2}{x_t}\right]^2 = \left[\frac{u_t u_g}{x_t}\right]^2, \tag{5}$$

$$\left(\frac{P}{S}\right)^2 + \left[\frac{Q_{max}}{S} - \frac{u_t^2}{x_t}\right]^2 = \left[\frac{u_t u_g}{x_t}\right]^2, \tag{6}$$

where the grid voltage (u_g) and the maximum grid reactive power (Q_g) must be known.

III. WORKED EXAMPLE

The worked example considers the vertically mounted, 103 MVA air-cooled hydrogenerator Åbjøra in Norway [12]. The rated power factor of this example is, $P/S = 0.9$, overexcited. Moreover, the hydropower unit is equipped with a Francis turbine with a maximum turbine power of 97 MW (e.g., $P/S = 0.94$). In addition, the TSO specifiy that all units in Norway shall be operated at $P/S = 0.86$, referred downstream the transformer to make room for reactive power reserves to be injected into the grid. If this machine was designed to operate at the TSO specifications, the maximum capability (necessary) to operate this unit with $\cos\varphi = 0.86$ with the rated turbine power is $\frac{97}{0.86} = 112.7$ MVA. This implies that the company will have an financial advantage with an upgrade of the rated power factor (e.g., 0.9) of the unit as it demands reduced size of the machine.

The diagram in Fig. 2 represents a boundary profile for a Synchronous Power Generating Module (e.g., hydrogenerator) defined by ENTSO-E. ENTSO-E (upstream) and TSO (downstream) requirements are visualized in Fig. 2. In addition, for comparison, the corresponding TSO upstream conditions are illustrated in the same boundary profile, calculated from eqs. (5) and (6).

Some aspects should be highlighted when the new ENTSO-E grid requirements are enforced on this unit e.g., the envelope in Fig. 2. This implies, the upstream condition, X/R ratio of the transmission line and infeasible operation point of the envelope. The maximum power of the machine is $P = 103 \cdot 0.9 = 92.7$ MW with a corresponding $Q_{max} = 45$ MVA and a $= Q_{max}/P_{max} = 0.48$ referred downstream the transformer and 1 p.u. voltage (11 kV), based on eq. (3). The values of both downstream and upstream are depicted in Table I, based on a 0.129 $p.u.$ step-up transformer reactance. In the procurement
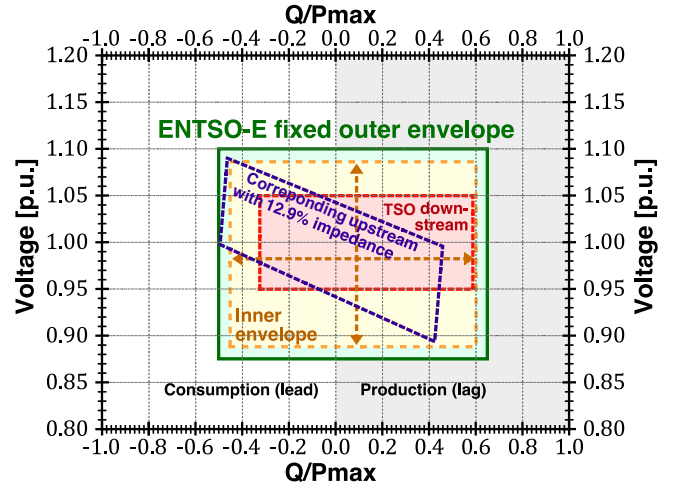

Fig. 2. Typical V-Q/P_{max} requirements of a synchronous power-generating module [11] from ENTSO-E. In addition, the TSO requirements for downstream and the corresponding upstream profile (referred Q/P_{max} at the generator side) are indicated. The TSO upstream profile impedance is based on the worked example.

TABLE I
RELATING THE DOWNSTREAM AND UPSTREAM FOR A) THE RATED VALUE OF THE 103 MVA GENERATOR, AND B) THE EXTREME MAXIMUM POINT OF THE ENVELOPE WITH A DOWNRATE OF P_{max} TO 0.8 PU OF THE UNIT.

Corner position	Downstream (t)	Upstream (g)
a) Voltage (u_t or u_g)	1.00 pu	0.95 pu
a) Reactive power (Q/P)	0.48 pu	0.34 pu
b) Voltage (u_t or u_g)	1.15 pu	1.1 pu
b) Reactive power (Q/P)	0.75 pu	0.65 pu

of the unit, a maximum (under-excited) of $Q/P = -0.33$ downstream with an SCR of $1/x_d = 1/1.087 = 0.92$ was designed. Typically, a unit operating in the Norwegian power system (depending on max. and min short-ciruit currents and stability margins) is designed with a $x_d < 1.2$. An adaption toward the ENTSO-E requirements (with e.g., $Q/P = -0.48$), could require a customization of the x_d to become significantly smaller (e.g., increasing the short-circuit currents). Further, the upstream point is connected to a 10 km radial 132 kV transmission line with a strong grid (e.g., infinite bus) on the other side. Typical voltage variation on this line is between 135 to 139 kV. The X/R ratio of the transmission line has an impact on the injection of reactive power.

The X/R ratio is often in the range between 7 and 15. Therefore, the reactive power losses $\Delta Q = 3XI^2$ is dominating over the active power losses $\Delta P = 3RI^2$. In addition, the thermal overload of the transmission line is strongly connected to the R of the line. With a low X/R ratio, an injection of reactive power quickly results in a rise in the voltage. On the other hand, a larger X/R ratio requires a larger amount of reactive power to cope with the grid losses. As the ENTSO-E requirements enforce a larger injection of reactive power by the unit, the grid system with large X/R ratio (e.g., 420 kV) and low step-up transformer reactance are preferable in such a case, and most likely the basis for the new requirements.
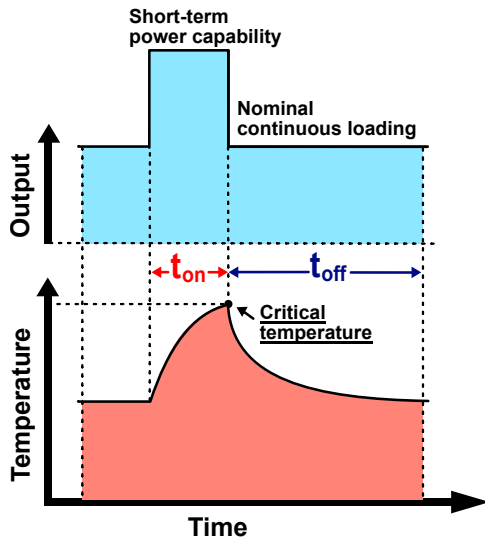
Fig. 3. Load cycle of the Extended capability diagram (ECD) [10].

The system with lower X/R (e.g., with the most of large hydrogenerator units in Norway) the new requirements are possibly too strict regarding continually operating points.

Another aspect is the extreme operating points of the ENTSO-E diagram. Firstly, consider the upper right corner (overexcited) of the envelope in Fig. 2. If the generator satisfies such an operating point, the P_{max} must be downrated to about 0.8 p.u. The primary side has to operate at a high voltage level of $u_t = 1.15$ p.u (12.65 kV) to carry out such operating point, which is outside typical machine design specifications of +- 5 %. Another challenging operating point is the low left corner (under-excited) of the envelope. In such a situation, the generator needs to work with unsatisfactory high stator current to provide the same power. In fact, the Stator Current Limiter (SCL) will over-rule such an operating point.

However, if the approach of utilizing an extended capability diagram [10], [12] is used, as illustrated in Fig. 3, extreme points may be realized in a shorter period of time (dynamic rating). This is mainly due to the large thermal inertia and the corresponding thermal time constants available in the machine. With new real-time monitoring and control technology [10], a dynamic envelop regime can be enforced on the generators. This approach would enhance the flexibility of the machine. In such a case, the OEL and SCL need to be replaced by this supervisory control structure [10]. The load cycle is depicted in Fig. 3.

Another approach is to carry out a redesign (upgrade) of the generator and the corresponding excitation system. In such a case, new design algorithms should be developed for an easy investigation of the worked example unit. As mentioned before, an improved solution can be to allowed by implementing OLTC on the step-up transformer for this unit, which appears to be the most cost-effective solution.

IV. New Operating Regimes

In Section II, a continuous loading condition was assumed. It refers to the IEC 60034-1 S1 duty standard depicted in Fig. 4, along with two other classical duty cycles (S2 and S3). However, Fig. 5 illustrates the ongoing shift in bulk power generation worldwide. The periodic and intermittent changes between different operation points indicate that the classical load cycles cannot any longer be trusted when the machine is designed from scratch. Fig. 5 highlights the unique case of generator-only condition for synchronous machines. Considering that the operating points are more and more distributed, the efficiency will be a significant differentiator. This is because the efficiency is strongly dependent on the MW-MVAr operating condition. In fact, at low active power, the ventilation, bearing and core losses will have a relevant impact on the generator efficiency. Moreover, the generator may operate as a synchronous condenser for longer periods with zero percent efficiency (according to the active power). As a result, the mean efficiency of the generator can get very low. It is perceived that the mean efficiency, in this case, represents a fictive issue, not a real issue, when dealing with the effect of new renewable energy penetration. This is because the generator is not operated to produce active power in the synchronous condenser mode of operation.

In addition to the variation in the stationary operating points, short and steep load ramps will also be absorbed by the synchronous generators. Besides, if an existing hydropower plant is to be considered, such a requirement may be unfeasible if hydraulic transients are to be considered from a stability perspective [14]; on the other hand, it may introduce remarkable challenges for new power plants design. However, by focusing the attention on the electrical side, the classical synchronous generators were designed for steady-state conditions according to several standards that did not take this into account, including C50.13 and IEC60034. In the future operating regimes, standards are needed to evaluate the equivalent efficiency and life-time consumption due to irregular operations, as a result of the energy transition (including the issue related to longer intervals of synchronous condenser operation). The nominal power is generally considered in the thermal ageing of the machine. As a result, the duty S1 (continuous running duty) is the default choice. However, it overlooks the differential thermal expansion of the generator when considering all MW-MVar fluctuations. Both thermal expansion and thermal ageing have an impact on the life-time expectancy of the machine. The predefined load cycles are practical if the load profile of the power plant is well known. In fact, the present machine standards are quite limited when considering the present evolution of the power system.

V. Conclusion

This paper presents the implications of new grid requirements on the classical synchronous generators. As shown, the reactive capability varies significantly between the upstream and the downstream of the step-up transformer. This issue leads to more challenges on the generator design, if not
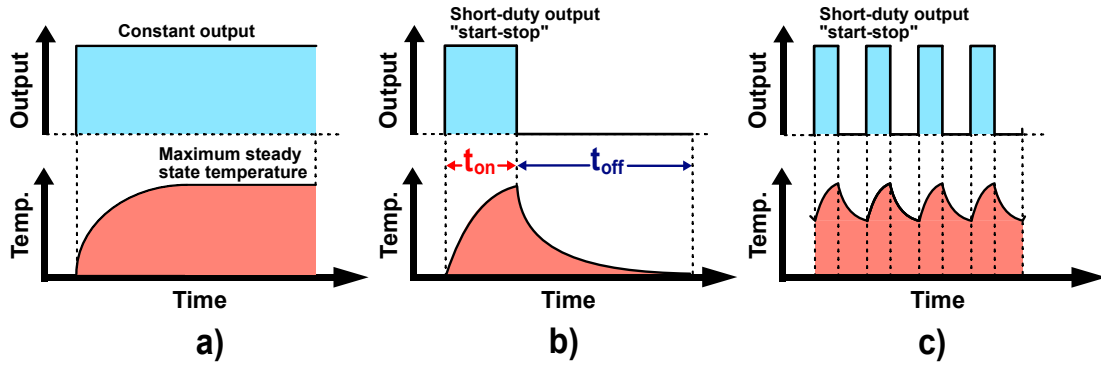
Fig. 4. Classical load cycles for electrical machines. **a):** S1 - Continuous running duty. **b):** S2 - Short-time duty. **c):** S3 - Intermittent periodic duty.
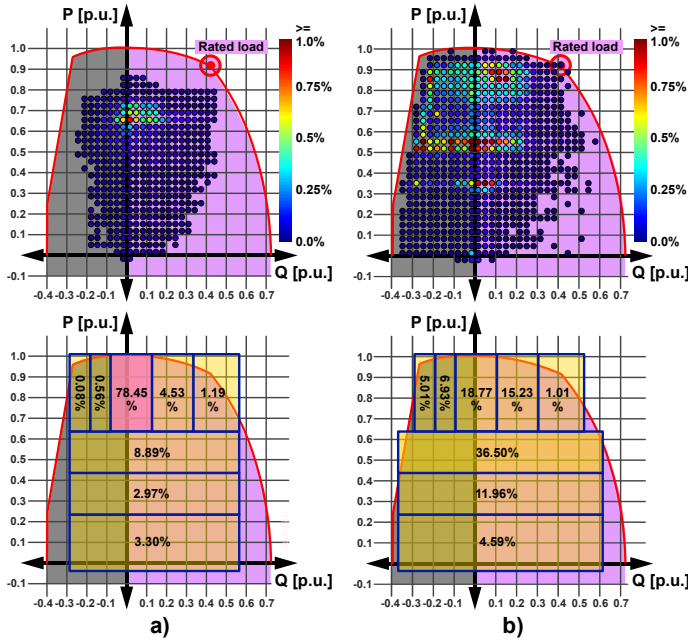

Fig. 5. Distribution of load points in the capability diagram of a 300 MVA generator, illustrating the relative changes due to the energy transition. **a)** Before the "German Energiewende" [6], [13]. **b)** After.

expansions occurring as a result of the energy transition. The lifetime and thermal ageing must be carefully considered when designing and operating the machines for future operating regimes. Finally, new design techniques must be developed as a consequence of the new operating regimes.

handled by a tap-changing step-up transformer. In addition to the steady-state reactive capabilities, this paper advocate for a dynamic reactive envelope for additional utilization of the generator (extended capability diagram). It can be used to provide short-term reactive reserves for grid security. Moreover, it is inevitable that the stricter requirements on the short circuit power of the generator lead to increased construction costs. However, the SCR may be lowered depending on the location of the generator. Other challenges include the fluctuations of the MW-MVAr condition, which lead to new issues with respect to efficiency, losses and cooling. The combination of MW-MVAr variability in on-load operation and synchronous condenser operation with zero active power is difficult to analyse from an efficiency point of view. Adaptive cooling will be needed to avoid the high ventilation losses under low loading conditions and to reduce the repetitive thermal

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