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Smart Transformer Use in Net-Zero Energy Factories

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SUMMARY

The integration of renewable energy in the electrical grid represents a challenge for system operators. To balance the volatility of energy generated by resources, such as wind and solar power plants, new flexibility options are necessary for safe grid operations. Due to the high investment costs and the high space that is demanded, energy storage systems might not be the only one solutions to increase the flexibility of the power grid. In this context, the concept of Net Zero Energy Factories might offer a significant contribution to the system operators. In Europe about 11% of factories (mostly small and medium enterprises) produce partially own electricity by solar energy. In almost all the cases, the generated electricity is fed into the grid. If they were operated as Net Zero Energy Factories, the generated electricity would be not more fed into the grid, but could be optimally consumed locally, smoothing also further power volatility for power systems operators. Within the Net Zero Energy Factories framework, realized also as a DC grid, the use of Smart Transformer represents a further efficient flexibility option.
This study aims to point out the main characteristics of Net Zero Energy Factories and gives detailed information about the use of Smart Transformer to increase the flexibility options set.

KEYWORDS

DC Grid, Energy Storage Systems, Net Zero Energy Factories, Renewable Energy Sources, Smart Grid, Smart Transformer

INTRODUCTION

Around 11% of small and medium-sized manufacturers in Europe use own solar panels to generate electricity [1]. In most cases, however, the electricity generated is injected into the main electrical grid rather than directly into the manufacturing grid and then successively withdrawn to cover manufacturers' electrical loads. This method of operating photovoltaic plants creates challenges for system operators that have to take expensive actions to compensate photovoltaic plants' volatile generation. This has been the approach in many European countries since the first photovoltaic plant went into operation twenty years ago. In Net-Zero Energy Factories (NZEF) framework, the electricity generated by volatile renewable energy sources (RES) is injected directly into the manufacturing grid instead of the main electrical grid [2]. This method of operating RES based power plants (e.g. photovoltaic plants) might become necessary when the Renewable Energy Sources Act, which economically incentivizes electricity generation by RES, expires. Operating a net-zero factory, however, necessitates taking advantage of load flexibility intrinsic to the manufacturing processes and/or planning new flexibility options (e.g. energy and material storage systems). In a NZEF, the electricity generated by RES may be used and stored in other energy forms (e.g. compressed air, heat or gas) that may be required in manufacturing processes. A NZEF can therefore be regarded as an industrial multi-energy system (MES). Operating manufacturing systems at net-zero requires an intelligent energy management system (EMS) [3], which must be well observable [4] including own flexibility offered by different options like electric vehicles [5]. Smart transformers (ST) with typical EMS functions of monitoring, forecasting and control could be implemented [6].

The power electronics-based ST [7] interfaces the MV and LV distribution grid to boost its controllability and to provide ancillary services. Several projects and prior studies have demonstrated the ST's capability to control load consumption by adjusting output voltage amplitude and frequency on its secondary side. This feature makes it possible to provide ancillary services such as soft load reduction [8], an alternative to firm load shedding, to support primary frequency control [9], to reduce synchronous generators' transient loads, to control overloads [10], and to prevent oversizing of the ST's hardware.

In this study, the increased control capability provided by the ST was introduced in the NZEF system. While the NZEF works to optimize a factory's intraday operations, the ST works with faster dynamics to optimize intrasecond or intraminute energy use in the factory. Connecting the ST to auxiliary equipment (e.g. air conditioning systems and heat pumps) or lighting systems makes it possible to manage their power consumption to obtain a net-zero condition in the factory.

Although the ST requires higher capital expenditure at first, the LV-ENGINE project [11] has demonstrated that, with infrastructure upgrade deferral, the ST could cut costs by as much as £ 60 million by 2030, which would translate into £ 500 million by 2050, while reducing the number of substations built by 2050by sixteen percent and preventing further disruption to customers.

SMART TRANSFORMER

The Smart Transformer is a three-stage power electronics transformer, enabling the voltage transformation from medium to low voltage levels and at the same time providing services to the grid [7]. Through its advanced control features, the ST is able to control the low voltage and

medium voltage grid independently, offering an ac power flow decoupling between the two grids. Several architectures and topologies have been considered for the ST application [12]-[13]. Despite the hardware differences, the ST control strategies do not differ substantially each other. Starting from the low voltage converter, the ST forms the voltage waveform in the fed grid (grid-forming mode), guaranteeing the highest power quality standards, independently from the demanded current (see Figure 1). If the low voltage converter is connected to another feeder through a Normal Open Point (NOP), the ST can still form the voltage. The power flow control will be achieved acting on the voltage amplitude and angle difference with the connected feeder. Alternatively, the ST can switch in a grid-following control (see Figure 1), where the injected power is controlled, and the voltage is a result of this control. The central stage, formed by a DC/DC converter absolves three tasks: adapt the voltage from medium to low voltage level; guarantees the galvanic insulation and controls the power flow between the two DC links. The last feature targets the DC voltage control in the low voltage DC link, controlling the absorbed power from the medium voltage DC link. The DC/DC stage can be fully [14], partially [15], bi-directional or uni-directional [16].
The medium voltage stage, composed by a multi-level converter [7],[12] due to the DC link high voltage (+10kVdc), controls the active power absorption from the grid, in order to balance the voltage in the medium voltage DC link. In this stage, the reactive power control is independent from the power request in the low voltage converter, and thus it represents a degree of freedom for providing support to the medium voltage grid.

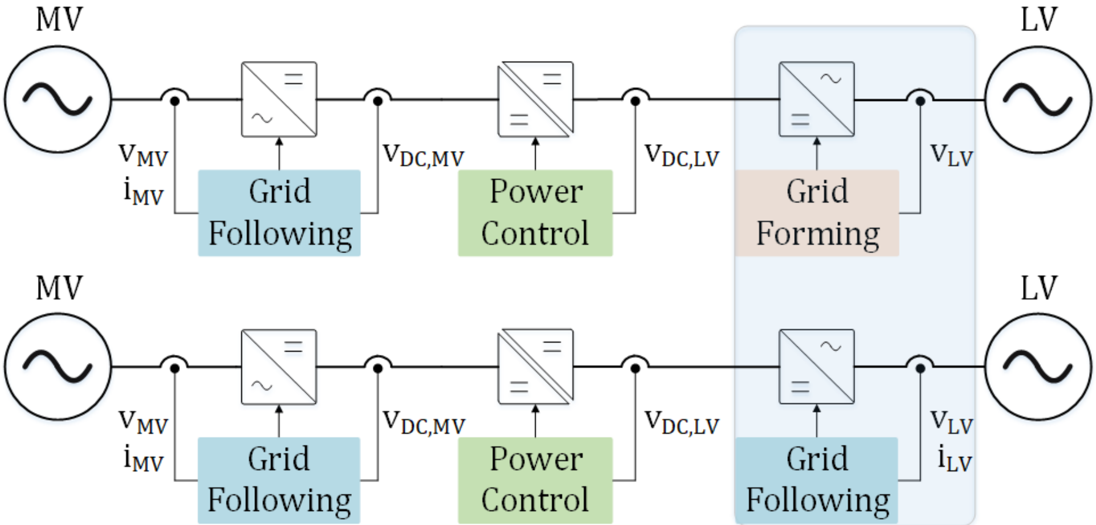

Figure 1 - Smart Transformer basic operations: the low voltage converter works as Grid-forming (top) and Grid following (bottom).

SERVICES AND ADVANCED CONTROLLABILITY OF ST

The Smart Transformer has not to be seen as a low-weight / small-size replacement of the conventional transformer. The power electronics allows an improved controllability of the grid, that is traduced in provision of more services. As can be noted in Figure 2, the range of offered services involves different voltage levels, and both ac and dc grids.
As an example, in the low voltage converter, the grid-forming characteristic offers more degrees of freedom in the grid control. As demonstrated in [8]-[10], the ST allows to vary the voltage amplitude, frequency and phase in order to interact with the voltage- and frequency-dependent loads. This possibility enables the on-line identification of the fed loads [17] (e.g., every few minutes), and the use of the power sensitivity to voltage and frequency information to apply more accurate control actions, such as the Soft Load Reduction [8], as alternative to fixed load shedding, or primary frequency regulation [9], to support the primary frequency control of

synchronous machines. If the ST is connected to adjacent feeders, it allows an optimal load sharing with the conventional transformer, avoiding possible overload conditions [18].
As far as the DC stage is concerned, the ST might represent the cornerstone for the development of a local (if low voltage) or regional (if medium voltage) DC distribution grid, enabling the connection of dc resources to the grid, without any intermediate AC/DC stage.
The ST medium voltage stage can provide reactive power support to the grid, working similarly to a STATCOM, without the need for additional space. It can correct the power factor at the HV/MV substation, or regulate the voltage profile along the mv feeder. Furthermore, it can work as active filter for non-linear loads (e.g., large machines, rectifiers), increasing the system power quality [19].

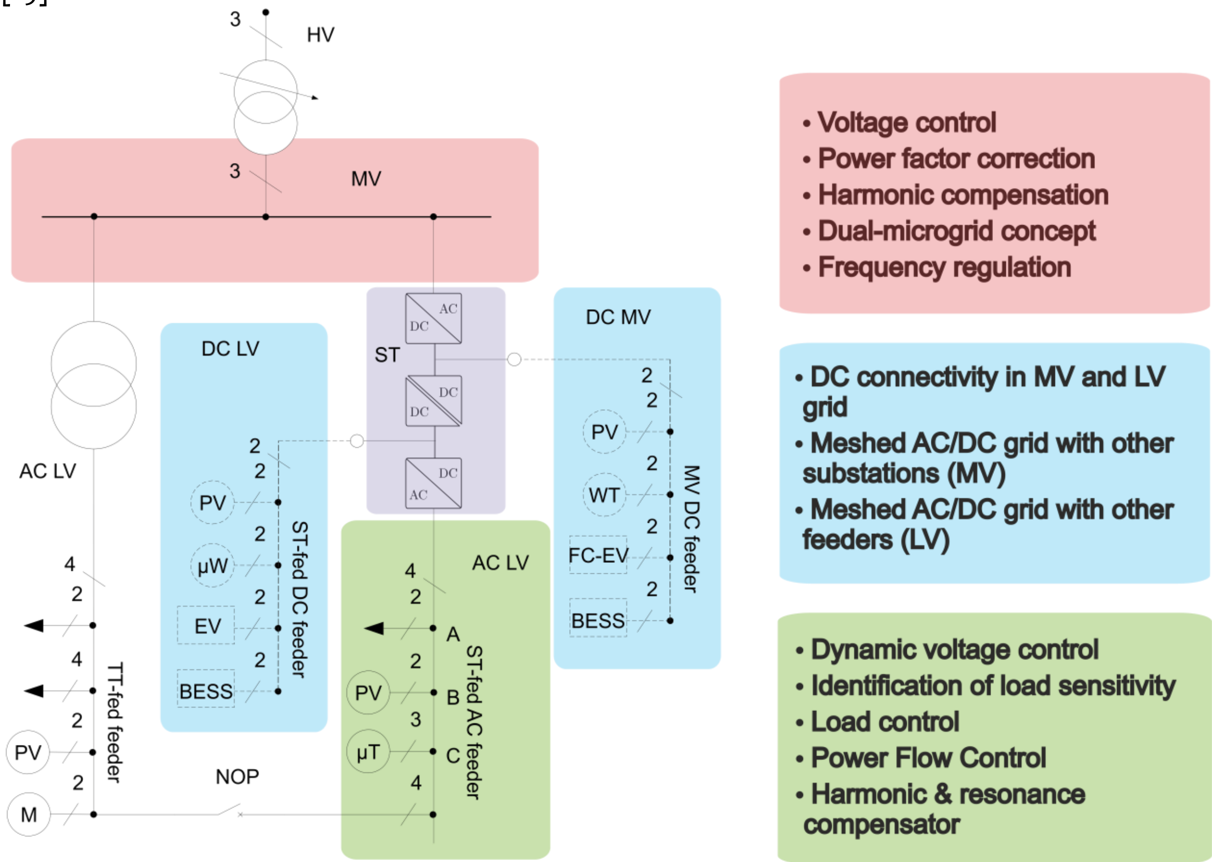

Figure 2 – Smart Transformer services for the distribution grid

NET ZERO ENERGY FACTORY CONCEPT

Net Zero Energy Factories (NZEF) are manufacturing systems able to locally produce electricity by RES and directly integrate it into manufacturing processes. The NZEF concept does not consider the option to feed electricity into the main grid in the case in which the power generated is higher than the power demanded. Therefore, in order to operate factories as "net-zero", flexibility options need to be identified, quantified and, if necessary, designed. To time, there are not standards able to directly identify and quantify the flexibility in manufacturing processes. A way to do that is to create mathematical models able to represent the energy and material flows as well as the technical and social (due to the workers) constrains [20]. Through the simulation of such models, the flexibility needed to match the power generated by RES can be identified and quantified. However, within manufacturing systems, many energy forms flow, such as electricity, compressed air, natural gas, heat and cold. In order to coordinate all these energetic forms, a holistic approach needs to be used [21]. Therefore, NZEF include the concept of industrial multi-energy systems (MES) in which the electricity is converted into other energetic forms through energy converters like heat pumps (for low enthalpy heat) and electrolysers (for hydrogen) or air compressor (for compressed air). In many MES concepts, the energy converters are combined together with energy storage systems. Therefore, the needed flexibility can be exploited through the control of the energy converters and of the energy storage systems [22]-[23].

Flexibility might also be exploited through the control of the manufacturing process. Indeed, many processes might be speed up, speed down or switched off without to effect the quality of the manufacturing process [24]. In this case, material storages play a fundamental role. Indeed the flexibility is mainly achieved by controlling the production rate (amount of manufactured products per time units) and the state of the charge of the material storage [2]. Figure 3 shows the structure of a NZEF. Different flows are depicted: material between production machines and material storage, energy flows (electric, compressed air and heat) and communication flow. Indeed, in order to operate the factory as "net-zero", a central energy management system needs to collect information about the generated electricity and the state of charge of the storages (energy and material), to predict their behaviour for the next time horizon and finally to control all the flexibility options.

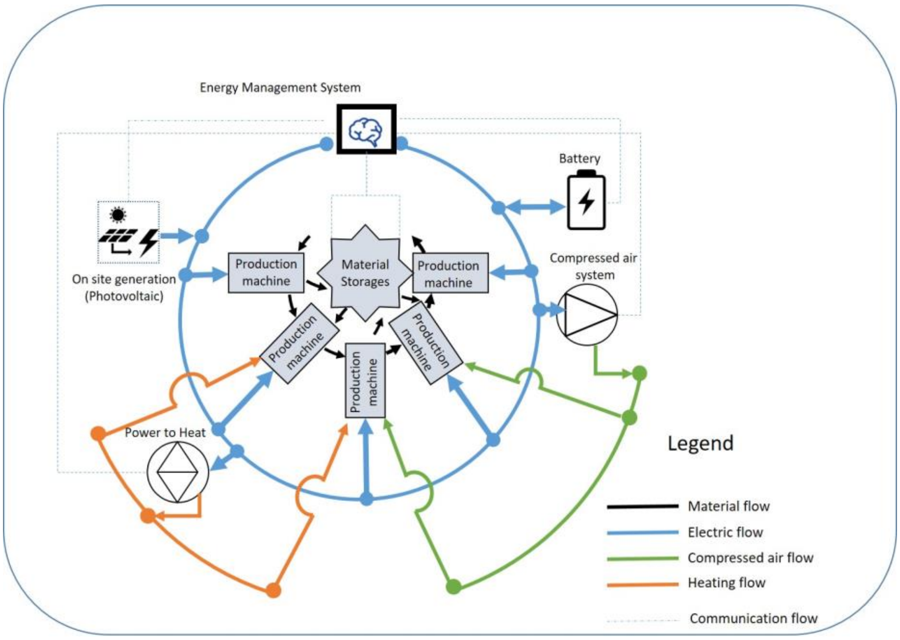

Figure 3 Structure of a Net Zero Energy Factory

APPLICATION OF SMART TRANSFORMER IN DC NET ZERO ENERGY FACTORIES

From the energetic point of view, the design of a NZEF can be approached in two ways. The first one consists to design the energetic flexibilities (i.e. batteries) using the pre-existing AC low voltage grid. Differently, the second approach considers the option to create a DC low voltage grid in which the energy generators (i.e. photovoltaic panels), the energy storage systems (i.e. batteries or compressed air) and the production machines are connected (see Figure 4). As characteristic of the second option, a Smart Transformer is used to control the DC grid.

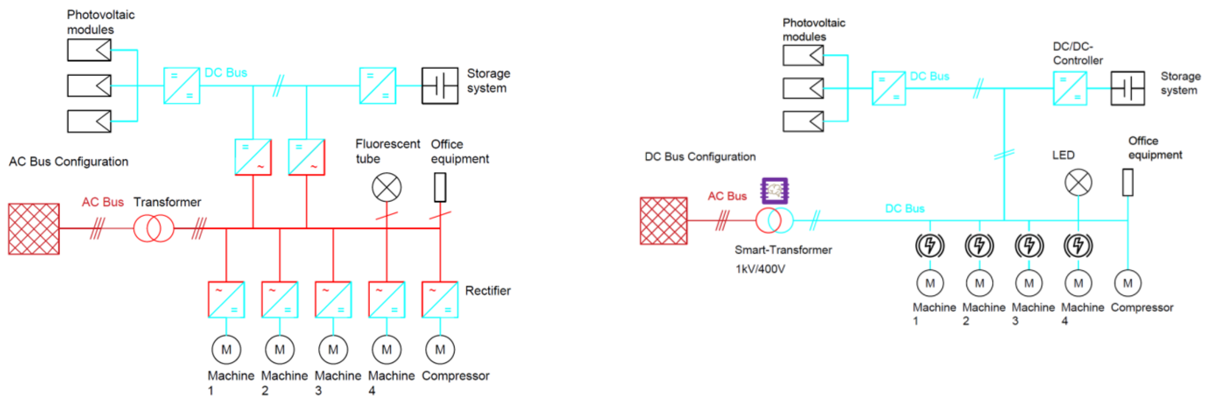

Figure 4 Net-Zero Energy Factory configurations :in AC grid (left) and in DC grid (right)

The design of a DC grid might be more expensive if compared to the AC solution. However, it offers the advantages to operate the system more efficiently. Indeed, efficiency might be gained through the elimination of the inverters and through the recovery of the energy during the braking phase of the machines. Besides it, the flexibility of the system might be increased by operating the voltage of the DC grid within a band between +10% and -15% of the nominal value. For DC grids in industrial application, a nominal voltage value of 648 V might be considered [25]. A ST might be therefore used to optimally control the voltage level, the energy storage system and the production machines. The optimal control might focus on the increase of the efficiency of the manufacturing system. Indeed, in case of oversupply, the ST might prefer to increase the voltage level instead to charge the energy storage system. Doing that, the losses of the energy storage system (about 20-30% [26]) might be reduced. Similarly, to the overload case, in which the ST might prefer to discharge the energy storage system only if the voltage level has already reached its minimal value. Behind to increase the flexibility degree, this way to control the NZEF might also affect the size of the energy storage system and therefore reduce the needed investment. However, the control of the voltage as flexibility option might have limit on application. Indeed the effect of the voltage control on the quality of the manufactured products needs to be further investigated.

CONCLUSIONS

About 11% of the European small and medium enterprises produce electricity through solar energy. The generated electricity might be directly integrated into the manufacturing system instead to be fed into the grid. This is the main characteristic of the concept Net Zero Energy Factories, which does not consider to option that electricity might be fed into the grid. However, in order to operate manufacturing systems as “net zero”, new flexibility options need to be planed and sized. The optimal control of the manufacturing processes together with the use of energy storage systems might offer the necessary flexibility to operate factories as net zero energy systems. However, the more efficient flexibility might be gained if the manufacturing system is realized as DC grid and if the voltage is controlled through a smart transformer. A Smart Transformer, due to its capability to shape the load consumption by means of controlled voltage variations, introduces new flexibility concepts in the Net Zero Energy Factories. Varying the DC voltage, the smart transformer can shape the voltage-dependent load consumption (e.g., constant current loads), thus introducing further energy flexibility, without recurring to continuous battery power cycling.

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