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Solid State Transformers for Ship's Electrical Power System

Abstract

Traditional transformers have an important role and a long history of use in shipboard power distribution systems. The introduction of fully integrated electrical propulsion systems and other high power nonlinear loads onboard modern vessels, together with increased number of ports with high voltage shore connection systems, causes considerable power quality issues which also affect the operation and the design process of traditional power transformers. Some of the challenges and shortcomings of conventional transformers can be partially overcome by using solid state transformers (SST). Thanks to the availability of advanced power semiconductor devices capable of handling medium voltage levels, there is a significant growth in the use of the SST technology in the smart-grid and traction application. This paper has analysed the possibility of SST implementation on ships.

Key words: Solid state transformer, ship, marine electrical power system, power quality, shore connection

1. Introduction

The complexity of ship electrical systems has increased considerably during several past decades. Ever growing demands for higher efficiency and environmental sustainability in the field of maritime transportation have led to the implementation of advanced electrical propulsion systems and a more complex electrical network with medium voltage (MV) generators and switchgear onboard modern vessels. Fully integrated electric propulsion systems have already become the standard choice onboard cruise vessels, LNG carriers and dynamically positioned off shore vessels, such as cable laying and drill ships.

The diesel-electric propulsion is a mature technology that has already reached its efficiency limit. In order for fuel consumption and ship emissions to comply with existing and future regulations, their further reduction can only be achieved by

implementing new technologies such as the use of energy storage devices, medium voltage DC (MVDC) distribution systems and high voltage shore connections, making ship's micro grids similar to shore side smart grids with large share of distributed energy sources. Such power systems are characterized by intensive use of power electronics which is necessary to provide more controllability of electrical drives and make the energy storage integration easier. Such nonlinear loads may cause serious power quality issues in weak grids like the ones used on ships.

All the above mentioned facts impose considerable challenges in the power transformer design. Transformers are essential components of MV electrical systems onboard commercial and navy vessels and can be divided into four main groups:

- distribution transformers,
- propulsion transformers,
- insulating transformers,
- low voltage auxiliary transformers.

Most marine power transformers are of the dry air cooled type, with or without forced cooling depending on their size. Liquid immersed transformers are very rare onboard sea going vessels due to increased danger of fire and explosion. General requirements for marine transformers can be found in [1].

In the context of application onboard ship, in choosing the appropriate transformer main focus should be on its size, efficiency, power quality and protection circuits. Main advantages of traditional LV transformers are high efficiency in the direct AC to AC conversion and short circuit current limitation. Disadvantages are losses at no load, sensitivity to harmonics, sensitivity to DC offset load imbalances, voltage drop under load and large volume/weight at low frequencies. Improvements in the development of conventional power transformers rely mainly on the development of new magnetic and insulating materials, yet the listed problems are still present.

Some of the weaknesses of LV transformers might be mitigated by using the solid state transformers (SST). A review of current advances in the SST technology can be found in [2, 3]. The purpose of this paper is to analyse the possibility of SST application in marine electrical power systems.

2. SST technology in the context of application onboard ship

The solid state transformer has recently gained importance as one of the most emerging technologies for future distribution systems, renewable electrical sources integration, railroad traction applications etc. The main idea of using SST onboard ship is to reduce weight and volume compared to traditional transformers by using power electronics to enable high frequency transformation from the medium to low voltage (LV) and isolation between two networks [4].

Since the large iron core is needed to avoid saturation at low frequencies, transformers (and in particular distribution and propulsion transformers) are usually

the largest components of ship's electrical power system. The transformer area product can be expressed as [5]

$$S_c S_w = \frac{\sqrt{2}}{\pi} \frac{P_t}{k_w J B_{\max} f} \quad (1)$$

where S_c is the area of the iron core cross section, S_w winding window area, J transformer winding current density, B_{\max} flux density amplitude, k_w transformer fill factor, f frequency and P_t transformer rated power. Relation between the transformer area product and volume can be expressed as [3]:

$$V \propto (S_c S_w)^{3/4} \propto \frac{1}{f^{3/4}} \quad (2)$$

Relation between the reduction of the transformer volume and the increase of the operating frequency when compared with 50Hz and 60Hz LV transformers is shown in Figure 1. Given the fact that an average vessel with the electrical propulsion system usually has as the minimum two distribution transformers and two propulsion transformers in the MVA power range (in practice, this number is usually higher) it can be seen that SSTs offer possibility of significant ship's space savings. It should be noted that the higher operating frequency also has negative side effects through the increased iron core and switching losses, which may reduce the SST efficiency.

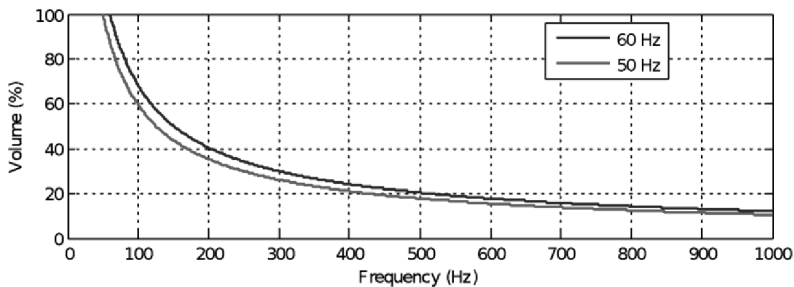


Figure 1 - Transformer volume vs. operating frequency

Unlike the traditional low frequency transformer, SST uses controllable power electronic circuits both on MV and LV side, allowing the reactive power compensation, voltage regulation, active filtering, power flow control and fault current limiting. Listed characteristics are very desirable in marine power grids because they make it possible for the unity power factor to be kept under the reactive load and for harmonics to be removed on the grid side, thus reducing the size and cost of main generators. The possibility of fast current limiting is very important not only for the protection of the system in general, but also for blackout prevention using fast load reduction schemes in the vessel power management system.

Another important feature of SST is modularity, which provides much greater freedom in choosing the accommodation space for transformer. Basic modular SST structures include DC link based topologies, direct/indirect matrix converters and hybrid combinations. The four most commonly used three phase modular SST arrangements (Figure 2) are [6]:

- fully modular three-stage SST with DC link and bi-directional converters on both the MV and LV side,
- three stage SST using indirect matrix converter on both the MV and LV side,
- two stage SST using direct matrix converter on the MV side and indirect matrix converter on the LV side,
- one stage SST using direct matrix converter on both sides.

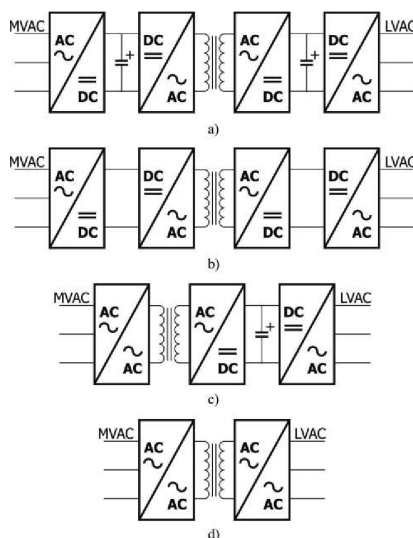


Figure 2 - Three-phase modular SST arrangements

Same as the conventional transformer, SST may be exposed to various fault situations, the most common for marine systems being: internal fault, switching transients, short circuit and load unbalance. Due to the complex structure of SST, there are far more possibilities of internal fault like semiconductor breakdown, control system failures, measurement failures etc. Another problem with SST is a limited capability of holding overcurrent due to the small thermal time constant of power semiconductors. Typically, SSTs are capable of holding 150% of the rated current for several minutes and 500% of the rated current just for a few milliseconds. Semiconductor devices are also very sensitive to overvoltage transients if they exceed their blocking voltage capabilities [7]. Due to limited overvoltage and overcurrent capabilities, SST requires additional

protection devices compared to standard LV transformer protection schemes. Another issue addresses the short circuit protection on the LV side since they need to provide the short circuit current to trigger protection relays, what is in direct contradiction with the aforementioned overcurrent limitation. To achieve the short circuit current and the inrush current limitation similar to the LF transformer, sufficiently large inductive filters are required on the MV side.

3. Possible SST applications in the marine power system

Since the SST has a lower efficiency in the direct AC to AC conversion and requires very complex protective schemes, its use has not yet been economically justified in traditional marine power systems with AC power distribution, except onboard vessels where small weight and volume are imperative.

Systems allowing SST to give its full potential are MVDC grids and hybrid propulsion systems with energy storage devices. Medium voltage onboard DC grid (MVDC) is the most promising technology for improving system performances on electrically propelled vessels because it eliminates the need for synchronization of primary electrical sources and bulky LF distribution transformers. It also allows generator prime movers to operate with variable speed depending on the load, which enables operation with a low specific fuel consumption in a much wider power range. Problems with harmonic and reactive currents are also eliminated. According to the IEEE 1709 standard, MVDC levels for future vessels will be 6, 12, 18, 24 and 30 kV [8].

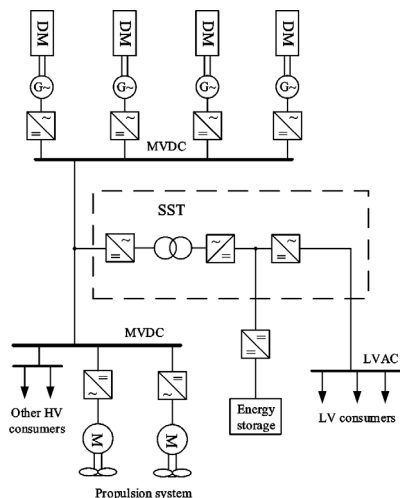


Figure 3 - Concept of onboard MVDC grid with modular SST

Characteristic features of MVDC grids facilitate the integration of different sources and loads like energy storage systems (e.g. batteries, flywheels or supercapacitors) and traditional AC consumers (e.g. induction motors, heaters, mooring winches etc.). Integrating components with so many different characteristics into one grid is not an easy task. The modular SST with a DC link is one of those technical solutions capable of meeting these demands. A single line diagram of the future MVDC grid concept which includes a modular SST is shown in Figure 3.

Another area where SST could considerably improve existing systems is the high voltage shore connection (HVSC) or cold ironing. This technology is used to limit ship emissions in port by connecting ship's electrical system to the land based distribution grid [9]. Cold ironing systems are hard to implement in European ports due to incompatibility of operating frequencies (50 Hz in the European distribution system and 60 Hz in ship's electrical AC grid). Expensive frequency converters and LV distribution transformers are required here as parts of the port infrastructure.

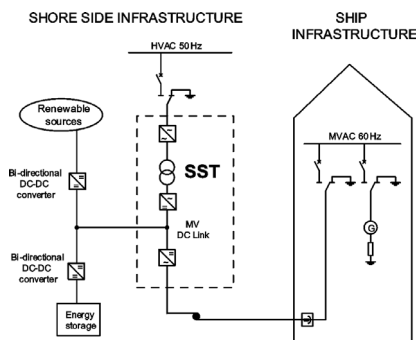


Figure 4 - Concept of HVSC system with modular SST

The modular SST could be an ideal solution for HVSC in Europe both for existing vessels and future vessels with the MVDC grid. It could also improve the efficiency of the port electrical grid by integrating energy storage and renewable sources like solar cells and wind turbines. The proposed concept for HVSC based on a modular SST is shown in Figure 4.

4. Conclusions

In this paper, most important characteristics of SST in the context of use in ship's electrical grids are reviewed. The use of SST technology can significantly reduce the size of the ship's electrical power system and increase power quality in grids with lot of reactive and nonlinear loads. In the traditional AC distribution system, SST has not yet been economically justified due to a lower efficiency in the AC/AC conversion and the need for additional protection devices. On the other hand, it is a promising solution

for future ships with the MVDC grid and HVSC systems in European ports because it enables the integration of sources and loads with different characteristics into one common grid, primarily energy storage systems. It can be concluded that despite its higher complexity and price as compared to LF transformers, SST technology can offer many more benefits in the marine power system and should be considered as a potential solution for increasing the efficiency and environmental sustainability of future ships.

Acknowledgements

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Primjena poluvodičkih transformatora u brodskim elektroenergetskim mrežama

Sažetak

Klasični transformatori imaju važnu ulogu i koriste se već dugi niz godina u brodskim elektroenergetskim sustavima. Korištenje potpuno integriranih sustava električne propulzije i drugih nelinearnih tereta velikih snaga na modernim plovnim objektima te povećanje broja luka s visokonaponskim kopnenim priključcima imaju značajan utjecaj na kvalitetu električne energije brodske mreže, a samim time i na radne karakteristike i dizajn transformatora snage. Neke od nedostataka klasičnih transformatora može se djelomično prevladati ili ublažiti korištenjem poluvodičkih transformatora. Zahvaljujući dostupnosti naprednih poluvodičkih ventila koji mogu raditi na sredjenaponskom nivou prisutan je značajan rast upotrebe poluvodičkih transformatora u području elektro vuče i pametnih energetske mreže. U ovom radu analizira se mogućnost upotrebe poluvodičkih transformatora na plovnim objektima.

Ključne riječi: poluvodički transformator, brod, brodski električni sustav, kvaliteta električne energije, kopneni priključak