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Potential and Impacts of Smart Transformer in Green Harbours

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***Abstract*—Harbour grids are undergoing rapid transformation due to the increased interest in green harbour initiatives such as ship cold ironing, renewable energy integration, battery-powered marine vessels, etc. In this scenario, better controllability over the power flow is important to maintain the voltage and current quality within the grid-code specified limits and ensure a stable and efficient power supply. This paper aims to explore the potential of the smart transformer (ST) in providing various support features to green harbours. The features include the integration and control capability of ST in accommodating renewable energy sources, electric vehicle charging stations and storage. In addition, the impact of the ST in the green harbour is analyzed with the focus of addressing the key issues and challenges such as voltage variations, peak loads and poor power factor.**

***Index Terms*—Green harbour, smart transformer (ST).**

I. INTRODUCTION

Moving towards the green harbour concept, the ship cold ironing has become a major load due to the advantages of the reduction of emissions while the ship stays at port [1], [2]. The integration of ship cold ironing loads will increase the load burden on the conventional grid structure. The battery-powered all-electric ferries are also getting attention being an environment-friendly alternative. For these ferries, the battery charging needs to be carried out at the harbour. Based on the size of the ferry and period of stay at the port, the charging power will be decided to provide demanded state of charge (SOC) before the ferry leaves the harbour. Various charging strategies for the modern marine vessel batteries are investigated in [3].

In addition to these transformations, the integration of renewable energy sources (RESs) and battery energy storage systems (BESSs) to the harbour grid also has importance to establish an emission-free harbour. As the harbour area uses various transportation options for the goods movement, the conversion of conventional fossil fuel-powered vehicle to the electric vehicles (EVs) also reduce the emissions. In this case, the integration of EV charging stations to the harbour grid is also an essential requirement. The interconnection of these assets leads to the creation of a microgrid structure at the harbour area [4]. Apart from these changes, conventionally the harbour area consists of many other indispensable loads. These loads include various motor drives for the movement of goods between different locations. The motor drives pose challenges such as the poor power factor (p.f.), harmonics and rapid change of loads. [5]–[7]. These challenges are addressed by using ultra capacitors (UCs) [8] and thyristor switched capacitors [5]. The static VAr compensators such as STATCOMs are also another option to provide power quality services [9]. Considering all these challenges, improved active, reactive and harmonic power management strategies are required to maintain the voltage and current quality within the grid-code specified limits.

Power electronics play a major role in the integration of various control features to the green harbour [10], and the smart transformer (ST) has the potential to provide these services. The ST is a power electronics-based transformer, and with the presence of DC buses at the medium- and low-voltage (MV and LV) levels, the ST has the capability to establish flexible interconnection between AC and DC grids [11]. The capability of ST is already explored in providing services such as voltage support [12], RES, electric vehicle charging station (EVCS) [13], BESS integration [14], and creation of meshed hybrid microgrids [15]. The load power control feature is another important service that ST can offer to the distribution grids [16].

Considering these issues and the capabilities of ST, this paper aims to identify the potential of ST in a green harbour for addressing various challenges. Different configurations of ST-enabled green harbours are considered, and their impacts in improving the grid operation are analyzed. The p.f. improvement, voltage support, and load control features are investigated in ST-based green harbour solutions.

This paper is organized as follows: The Section II describes the conventional harbour configuration. In Section III, the control capabilities of ST is explained. The Section IV discusses configurations of ST-based green harbour. The impacts of ST in green harbour is analyzed in Section V, and Section VI concludes the paper.

II. CONVENTIONAL HARBOUR GRIDS

The single-line diagram of a simplified harbour power distribution system is shown in Fig. 1 [3]. The loads are divided into the ship cold ironing loads and harbour loads. The conventional distribution transformers (CDTs) are used

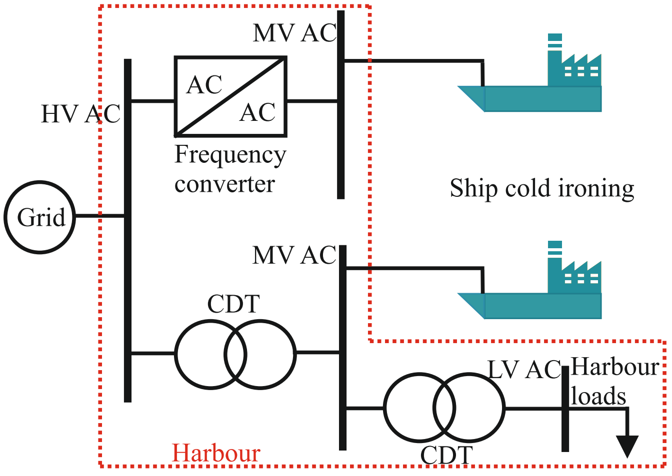


Fig. 1. A simplified harbour power distribution system derived from [3].

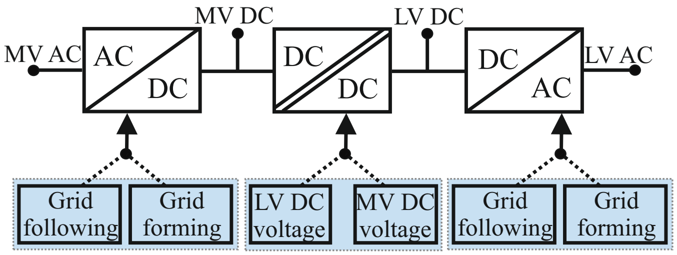


Fig. 2. The ST and control capabilities [15].

to achieve different voltage levels that are required to connect different type of loads. The frequency of ship electrical power distribution varies in different cases. Therefore, a frequency converter at the harbour ensures universal connectivity for all types of ships. The frequency converter is integrated to the harbour in various topology configurations depending on various factors such as maximum power demand, voltage level requirement, etc. [17]. The major shiploads vary from different motor drives to lighting and air conditioning loads depending upon the type of ship. For example, the reefer container ship carries goods that require continuous refrigeration, therefore, the major electrical load would be for air conditioning. Similarly, the dominant load in a passenger ferry would be lighting and charging of battery storage systems. The larger ships require a relatively high amount of energy, and during the peak load periods of the grid, it can introduce voltage deviation and asset-overload condition in the grid.

The major harbour loads are motor drives required for the cranes to transport various goods between ship and shore. These cranes usually follow a rapid load changing pattern during the completion of a cycle of operation [6]. These load changes create variation in voltages as well as larger impulse in load curve. In addition, the low power factors of these drives are also a concern. In this scenario, to incorporate various integration and control capabilities for the green harbours, the ST is found to be a potential solution.

III. CONTROL CAPABILITIES OF ST

The different control possibilities for ST converters are shown in Fig. 2 [15]. The three-stage ST architecture consists of an MV converter as the first stage that connects between MV AC and MV DC buses. The second stage is an isolated DC-DC converter that connects between MV DC and LV DC buses. In the final stage, the LV converter connects between LV DC and LV AC buses. In the basic operation that emulates a CDT, the ST MV converter works as a grid following AC-DC converter with the provision of MV DC-link voltage control. The ST DC-DC converter provides the necessary isolation and maintains the power flow between MV and LV DC buses by controlling the LV DC-link voltage at the specified value. The ST LV converter works as a grid forming DC-AC converter that maintains a three-phase balanced voltage at the LV AC grid. The ST control is flexible, and can be adapted depending on the respective application, e.g. focusing on the support to either MV or LV AC as well as to the integration of storage units at the DC terminals. This paper utilizes these control capabilities for investigating various benefits ST can bring to a green harbour. The following part illustrates the capability of the ST to reconfigure the harbour grid in multiple forms.

IV. CONFIGURATIONS OF ST-BASED GREEN HARBOUR

As the conventional harbours are getting transformed to green harbours with the environmental friendly initiatives, the integration of BESS, RES and EVCS are inevitable in the green harbours. In addition, accommodating the harbour and ship loads with better controllability requires the help of power electronic converters. The ST can provide a solution in this scenario. In the configuration shown in Fig. 3(a), the ST is used for connecting the harbour loads. The LV DC link of ST is used for the integration of BESS, RES and EVCS. However, in this configuration, the ship cold ironing loads are supplied either through a CDT or with the help of a frequency converter similar to the configuration shown in Fig. 1.

This configuration is further modified in Fig. 3(b). Here, the frequency converter is eliminated, and the ST MV converter is used for connecting the ship cold ironing load. An additional AC-DC converter is used to form a connection to the MV DC link of ST, thereby forming a power electronic interface for connecting different frequency ships to the green harbour. The ST is used along with the CDT to supply the harbour loads similar to the configuration shown in Fig. 3(a). The BESS, RES and EVCS integration is realized with the LV DC link of ST. In the following section, different case studies are considered to analyze the impact of these ST configurations on the green harbour.

V. IMPACT OF ST IN GREEN HARBOUR

To understand the impact of ST in the harbour grid, various challenges are considered, and the ST's capability to provide the support is studied.

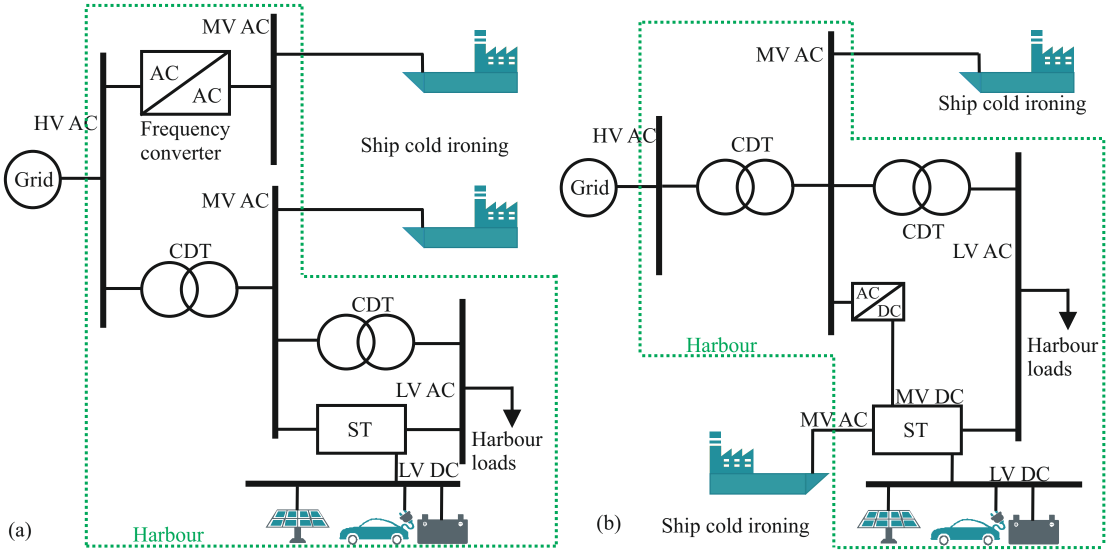
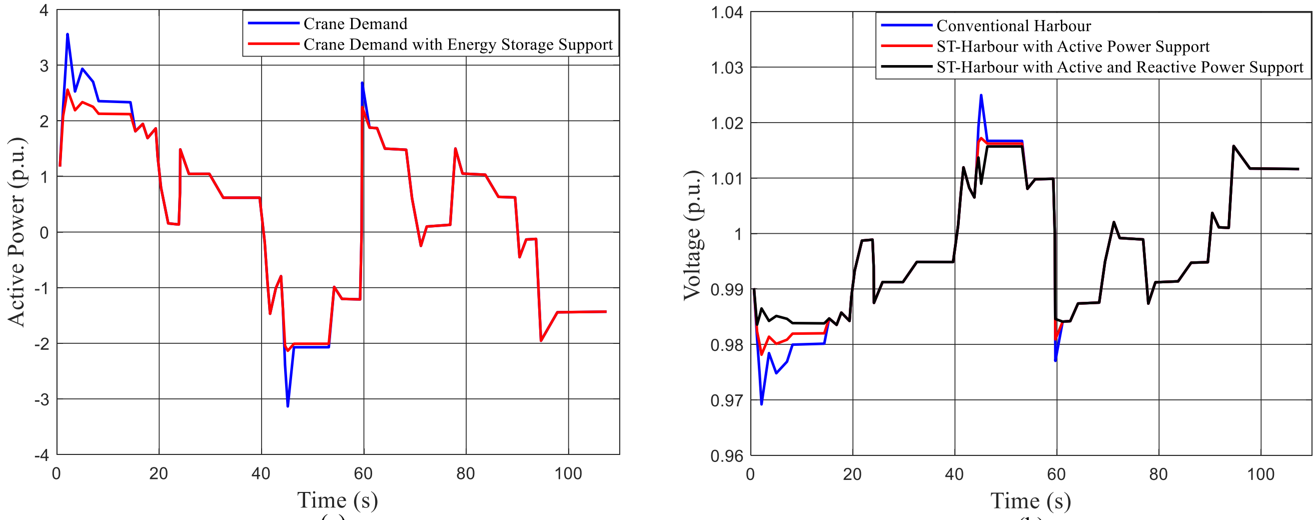


Fig. 3. Proposed ST-based harbour solutions. (a) The ST used only for harbour loads. (b) The ST used for both harbour and ship loads.



(a)

(b)

Fig. 4. Impact on harbour grid voltage. (a) The harbour crane demand with and without ST-based energy storage support. (b) Voltage variation in harbour PCC due to the crane load.

A. *Impact on the Voltage at Harbour PCC*

The voltage at the harbour PCC is affected by the load active and reactive powers. The voltage at the harbour MV AC PCC ($\mathbf{V_h}$) is related with the main grid voltage ($\mathbf{V_g}$) as

$$\mathbf{V_h} = \mathbf{V_g} - \left(\frac{P_h - jQ_h}{\mathbf{V_h^*}}\right)(R_g + jX_g) \qquad (1)$$

where P_h and Q_h are the harbour load active and reactive powers, respectively. The total grid resistance and reactances are given as R_g and X_g, respectively. The ST provides the reactive power to the harbour loads. Therefore, the grid supplies only active power to the harbour loads. In addition, the active power support from the BESS, and reactive power support from ST MV converter also improves the voltage. As a case study, the crane operation provided in [6] is considered. The load pattern for completing a cycle of operation is shown in Fig. 4(a). The crane loads follow a rapid changing pattern with peak loading and regeneration happens during the cycle of operation. The base quantities for power and voltage are considered as 1 MVA and 11 kV (L-L), respectively.

In the base case, the conventional harbour configuration shown in Fig. 1, is considered and the crane loads are connected to the LV AC bus of the CDT. Even the harbour cranes would be operating at a lagging power factor, for this analysis, a unity p.f. operation is considered. Therefore, the impact on voltages would be higher than this analysis in the actual practice.

In the ST-based harbour configuration shown in Fig. 3(a), the BESS supports the active power during peak load and regeneration conditions of the crane operation. This is incorporated through a droop based BESS power dispatch control. The BESS discharge is activated when the active power load exceeds a pre-defined limiting value. During the high load condition, the BESS power discharge (P_{db}) is given by

$$P_{db} = \begin{cases} 0 & \text{if} \quad P_h \leq P_{l-\text{lim}} \\ (P_h - P_{l-\text{lim}}) * m_{lb} & \text{otherwise} \end{cases} \tag{2}$$

where $P_{l-\text{lim}}$ is the limiting active power load, m_{lb} is the droop coefficient for active power dispatch. Similarly, during regeneration scenario, the BESS absorbs (P_{cb}) the excess active power in the similar strategy given by

$$P_{cb} = \begin{cases} 0 & \text{if} \quad P_h \geq P_{g-\text{lim}} \\ (P_h - P_{g-\text{lim}}) * m_{gb} & \text{otherwise} \end{cases} \tag{3}$$

where $P_{g-\text{lim}}$ is the limiting active power generation, m_{gb} is the droop coefficient for active power absorption. With the energy support, the load curve follows a pattern with reduced peaks as shown in Fig. 4(a).

In addition to the active power, the ST also supports the grid with reactive power from ST MV converter during the peak load and regeneration period. The reactive power injection from ST MV converter is also facilitated using the droop control similar to the BESS power exchange. The voltage at the harbour PCC is plotted in Fig. 4(b). The curves with active power alone and combined active and reactive powers show the improvement in voltage magnitudes in the ST-based green harbour. The load active power and PCC voltage curves show the capability of ST-based green harbours in controlling the peak load as well as the voltage variations. This analysis does not consider the effect of p.f. on the grid operation. The following section analyzes the impact of the ST based green harbours on the poor p.f. related issues.

B. Impact on the Power Factor

The harbour crane motor drives use AC or DC drives. In spite of the advantages of DC drives, the p.f. is an issue that needs to be addressed in the installation of DC drives. The poor p.f. has adverse effects on voltage, active power losses, and kVA loading of the line and transformers. Further, the poor p.f. leads to the penalty to the harbour from the grid operators. The p.f. correction devices such as thyristor switched capacitors, static compensators, etc. are proven solution for integrating these features [5]. In this scenario, the ST-based green harbour can also provide these services to the harbour grid. The improved p.f. operation of the harbour grid in turn improves the load hosting capacity of the cables and transformers without additional infrastructural reinforcement.

As the poor p.f. operation increases losses in distributing the power to the harbour, the ST based harbour shown in Fig. 3(a) can reduce the losses by improving the p.f. The energy losses are associated with the increased cost of energy. The percentage savings in energy costs are directly proportional to the percentage reduction in losses and is given by

$$\%\ \text{reduction in losses} = \left(1 - \left(\frac{\text{original p.f.}}{\text{corrected p.f.}}\right)^2\right) \times 100. \tag{4}$$

The percentage savings in cost of energy is plotted against the original p.f. in Fig. 5(a). Lower the original p.f., larger savings are possible with the ST-based green harbours. Further, the poor p.f. demands higher ratings for the electrical assets such as cables and transformers. Therefore, the ST-based green harbour can get benefit by avoiding or deferring the asset restructuring for accommodating more loads. The ratings of these infrastructure is related to the apparent power demand. In Fig. 5(b), the rating requirements for the assets are plotted with the variation of crane p.f. for a 1 p.u. of active power load. The lower p.f. operation demands for a higher rated assets. In addition, Fig. 5(b) also shows the variation of increase in cost of restructuring with respect to changing p.f. The percentage increase in cost is calculated with respect to the unity p.f. operation. As seen in the curve, the ST-based green harbour provides higher savings in the lower p.f. conditions.

C. Capability of Load Power Control

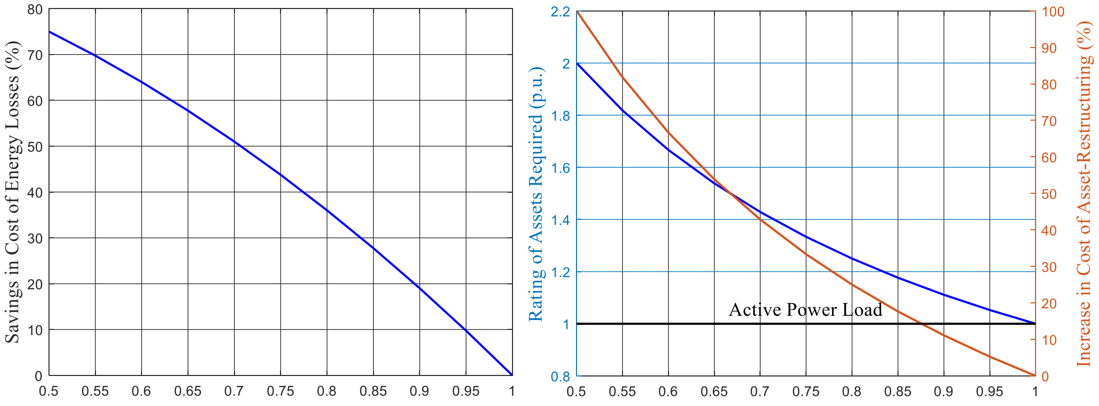
In Fig. 3(b), the ST is used for ship connection through the asynchronous MV DC connection link. In this mode, the ST MV converter establishes the voltage required for the ship cold-ironing connection. This is realized by the grid forming control of the ST MV converter [15]. The voltage dependency of the ship active power loads is expressed as [16]

$$P_r = P_n \left(\frac{V_r}{V_n}\right)^{K_p} \tag{5}$$

where P_r and P_n are actual and nominal loads, respectively. The sensitivity coefficient is given by K_p, and the actual and nominal r.m.s voltages are given as V_r and V_n, respectively. This operation is considered as an electric spring in the network.

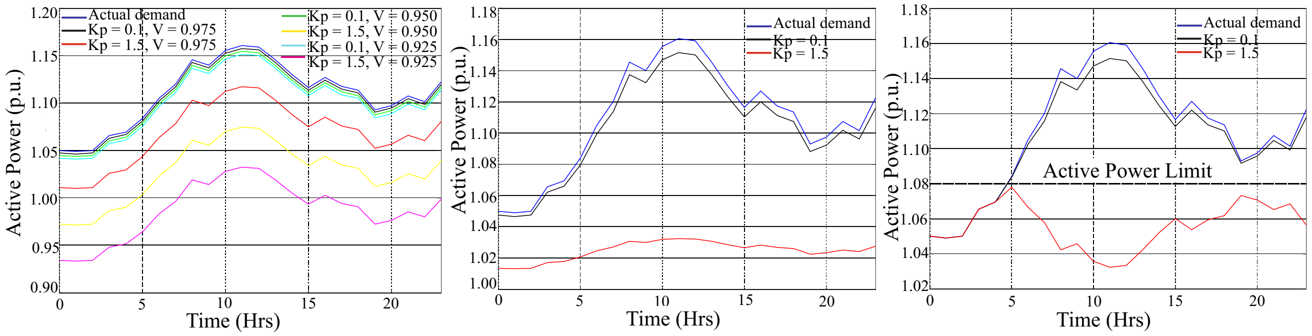
For analyzing the impact of load power control on the ship cold ironing loads, a case study is considered. The average ship cold ironing loads for the period of one day is provided for the port of Barcelona in [18]. The loads are normalized to per unit (p.u.) considering a base of 200 MVA. Considering this load variation, the load power control capability of ST-based green harbour shown in Fig. 3(b) is studied. In this case, three different methods are used for the load control. In each of the methods, two load sensitivities are considered for the analysis, 0.1 (eg: industrial loads) and 1.5 (eg: winter heating loads), respectively [19]. The selection of these two extreme magnitudes of sensitivities ensures that the analysis covers the worst and best possible scenarios in load voltage dependency. The minimum voltage used for the load control in this analysis is 0.925 p.u.

In the method-1, the ship cold ironing loads are applied with the constant lower voltage throughout the period of the day. Different voltage and sensitivity combinations are plotted



(a) (b)

Fig. 5. Impact on harbour grid power factor. (a) Percentage savings in energy losses in line for ST-based green harbour in comparison with conventional harbour configuration during low power factor operation. (b) Apparent power rating of assets required and percentage increase in cost of asset restructuring.



(a) (b) (c)

Fig. 6. Impact on harbour grid load control. (a) Load variation in method-1. (b) Load variation in method-2. (c) Load variation in method-3.

TABLE I

THE SAVINGS IN COST OF ENERGY USING ST-BASED GREEN HARBOUR WITH LOAD POWER CONTROL.

Method	Method 1						Method 2		Method 3	
Voltage at ST terminal [p.u.]	0.975		0.95		0.925					
Sensitivity coefficient	0.1	1.5	0.1	1.5	0.1	1.5	0.1	1.5	0.1	1.5
Savings in cost of energy [%]	0.25	3.73	0.51	7.4	0.78	11.04	0.53	7.63	0.33	4.83

in Fig. 6(a). The variation of actual and controlled demands are shown in p.u. for the entire duration of the day. From the graph, it is evident that, a maximum load reduction is possible with a combination of voltage magnitude of 0.925 p.u. and load sensitivity of 1.5. Similarly, a minimum load reduction is possible with a combination of voltage magnitude of 0.975 p.u. and sensitivity of 0.1.

In method-2, the voltage is varied dynamically between 0.925 and 0.975 p.u. based on the real time load conditions. The minimum load is considered as 1 p.u. and the voltage of 0.975 p.u. is applied for this load. For the maximum load, 0.925 p.u. voltage is applied to have a maximum load reduction. For the other loads, the voltage is dynamically varied. The actual demand and modified demands for the load sensitivities of 0.1 and 1.5 are plotted in Fig. 6(b).

In method-3, similar to method-2, the voltage is varied dynamically. However, the voltage is maintained at 1 p.u. for low load periods. An active power limit is defined, and the dynamical variation of voltage starts from this limit. Therefore, the load control is not applied throughout the load curve. The variation of the ship load demand for different period of the day are shown in Fig. 6(c).

From this analysis, the per day energy consumption in the harbour is calculated for different cases. In the base case, the actual load profile based on the Barcelona port is considered [18]. A constant cost profile for the energy is assumed. In comparison to the cost of the energy in base case, the percentage savings for each case are given in Table I. For each method, scenario corresponding to two sensitivities are considered. For method-1, a maximum of 11.04% and minimum of 0.25% of cost of energy can be saved based on the load sensitivity and voltage applied.

Conventionally, these services are available from different individual solutions. However, the analysis shows, the ST is capable of performing as an integrated solution for addressing these individual challenges. The ST-based green harbours provide solution for RES, BESS and EVCS integration challenges along with improving the load active and reactive power control capability.

VI. CONCLUSION

This paper studies the impact of ST in green harbour. The renewable, storage, and EV charging integration capability of ST opens up a solution for the "green harbour" initiatives. The ST-based green harbour configurations provide the peak load management services with the capability to control the voltage variations. In addition, the power factor correcting services provide the advantages in deferring or avoiding the asset strengthening measures that provides economic advantages to the harbour grid operators. The ship cold ironing integration using ST avoids the use of frequency converter in the port. Further, the ST load control capability is applied in such configurations to reduce the energy costs associated with the ship-cold ironing. The analysis shows that the load control capability can provide a maximum of 11.04% of energy savings in an ST-based green harbour. It can also work similar to an electric spring in the network to provide flexibility in peak load management.

VII. ACKNOWLEDGMENT

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