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Intelligent DC Microgrid Living Laboratories - A Chinese-Danish Project

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Abstract—This paper presents a research project focus on the development of future intelligent direct-current (DC) microgrids which is being deployed for highly efficient integration of distributed generation and modern electronic loads. The project is based on the collaboration between research institutes in China and Denmark, aiming to explore the different aspects of DC microgrids: design, modelling, control, coordination, communications and management. In addition, a future Living Laboratory will also be integrated into the Intelligent DC Microgrids Laboratory, which will serve as demonstration facility for low voltage direct-current (LVDC) distribution systems. Research is carried out in both Intelligent DC Microgrid Laboratories, focused on industry in China and residential applications in Denmark.

Keywords—Microgrid, Smart homes, Smart grids, Energy Management.

I. INTRODUCTION

Future electrical distribution systems will use more direct current (DC) architectures. Practical efforts that support this global trend can already be seen in US, Japan, and Korea, through efforts of conceptual design and demonstration projects for low voltage DC networks [1]–[4]. In that sense, it seems that EU countries are lagging behind the competition. Starting a similar initiative in Denmark will contribute in making it a region leader in developing conceptual and industrial solutions for this fast growing market. The first and a more natural step for this revolution is to develop residential and industrial DC-based microgrids.

There are several well-known features offered by the DC technology, which can significantly enhance the efficiency and energy savings, and power quality and reliability of the distributions systems, that have recently drawn the attention of the research community. These features are summarized below:

- First of all, distribution in DC is intrinsically more efficient than AC, because in DC there is no reactive power.
- DC loads can represent 50% of the whole building [5], and since most of the electronics power supplies use a two-stage conversion topology (first AC-DC and then DC-DC), supplying the DC loads with a DC distribution system would avoid an unnecessary

AC-DC conversion stage, and therefore increasing the overall efficiency.

- Distributed energy sources suitable for implementation at residential level as, PV panel and fuel cells, are DC sources. Hence a DC distribution system is more convenient for the distribution of energy generated by DC sources. The efficiency and energy saving are further increased if the energy produced by the distributed energy sources, is used to feed the DC loads.
- Typical energy storage systems for residential applications as batteries or supercapacitors, are also DC devices, and again the use of a DC distribution system would decrease the conversion stages and therefore increase the efficiency.
- The recent growth of research, development and implementation of electric vehicles charging stations, shows a trend of which the electric vehicles would be widely integrated into the electrical grid, mainly at residential levels, which would increase the DC loads consumption.

These potential energy savings of DC distribution systems for residential applications have been studied in [6]–[9]. Also, Lawrence Berkeley National Lab (US) has shown that a system efficiency enhancement, between 10% and 30%, can be achieved, in addition to a decrease of 6% in terms of cost; DC power systems could offer additional savings by eliminating the AC-to-DC conversion losses for DC loads, which constitute on average 14% of the AC load. The studies have shown the potential energy savings from 5% to 30% when using LVDC distribution systems. The potential savings differ much since different implementation scenarios were evaluated. In [6], two different power architectures, with and without energy storage, are evaluated in different locations across United States. The DC distribution system with no storage would barely increase the efficiency 5%, because the differences between the peaks of consumption and production. For instances, the solar production peaks at noon while the consumption peaks in the morning and in the afternoon. Therefore, sending most of the generation directly to the grid, through a DC distribution system, does not bring great energy savings. However, the use of a storage system could yield to energy savings up to 14%. In [7], a previously analysed study was further developed, including the effect of a load shifting strategy and the integration of the

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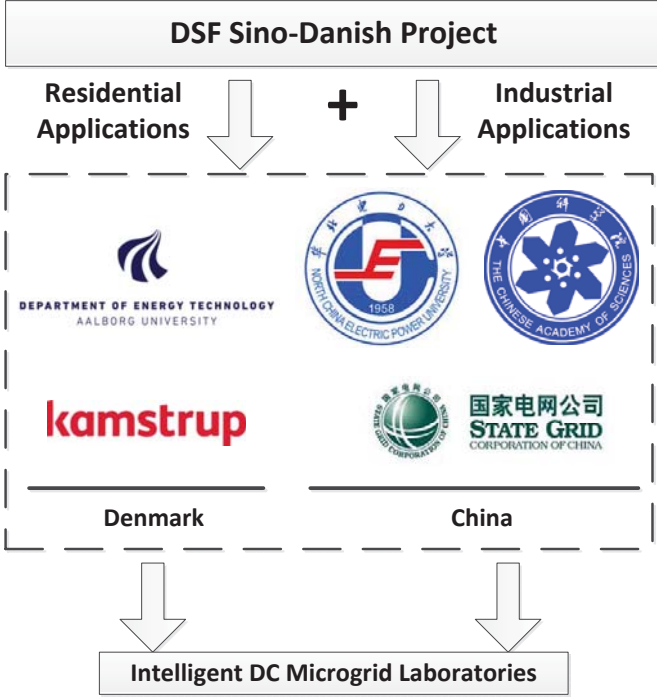


Fig. 1: Description of the Chinese-Danish Collaboration Project.

electric vehicle. Both scenarios have shown a marginal increase of the energy savings, because the electric vehicle was charged during the nights, hence, the energy was coming from the AC grid and not from the PV panels, also, a two-hour shifting of the cooling load to better match the PV generation profile barely improve the efficiency. In [8] and [9], greater potential energy savings are obtained, 25.3% and 30% respectively, leading to a reduction of the United States consumption by 2.98%.

Energy savings have been already achieved by implementing LVDC distribution systems in commercial datacenters [10], [11]. Also, the current emergence of DC power standards and products designed for grid-connected residential and commercial applications creates high expectations for the future commercial use of this technology.

Nevertheless, the studies regarding residential applications need to be validated through experimental implementation. A second project is also being developed in parallel at AAU, which intends to build a Living Laboratory for the demonstration of intelligent distributions systems for residential applications. The Living Laboratory is a module with two fully-equipped residential apartments, where a low voltage DC distribution system will be implemented in one of the homes. The Living Laboratory will provide experimental profiles of energy production and consumption, for both, AC and DC systems, aiming to validate the potential benefits of DC microgrids for residential applications.

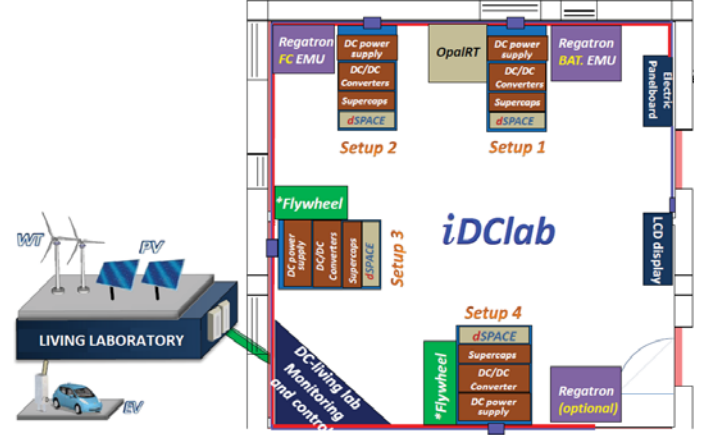


Fig. 2: Schematic of the Intelligent DC Microgrid Laboratory.

II. MICROGRID LABORATORIES IN AAU FOR RESIDENTIAL APPLICATIONS

A. Intelligent DC Microgrid Laboratory

In the Energy Technology Department of Aalborg University (AAU), a laboratory focused on DC microgrids for residential applications will be established. The facility will be used as a research platform, in order to perform all the necessary steps to shift the technology from laboratory scale to real industry. The project will enable the AAU Microgrid Research Group to gain a first-hand experience in developing the future electrical distribution systems which include power hardware infrastructure, integration of ICT technologies and deployment of intelligent energy management strategies that takes into account the variable grid price. The added knowledge will create competitive advantages and more visibility of Danish research and industry.

Fig. 2 shows the distribution of the Intelligent DC Microgrid Laboratory (iDCLab) and its connection with the Living Laboratory. The facility consists on several setups, each one of them with the following components:

- A real-time digital module that allows a model-based control design, which minimizes the implementation time of new control strategies.
- Four bi-directional DC/DC converter EZA2500, manufactured by TDK-Lambda [12], which will be controlled through a real-time platform control desk.
- Constant power loads.
- Energy storage systems.
- Smart meters.
- Multiterminal medium voltage connections.

In every setup is possible to develop various configurations, in order to emulate and analyse the microgrid behaviour, where end-user appliances and smart-grid ready technologies will be used. Also, a combination of photovoltaic systems, wind power generators, batteries, electrical vehicle chargers, LEDs, and other non-conventional DC appliances such us DC washing machine, DC cooling fans, DC oven, DC-TV and so on will be tested together.

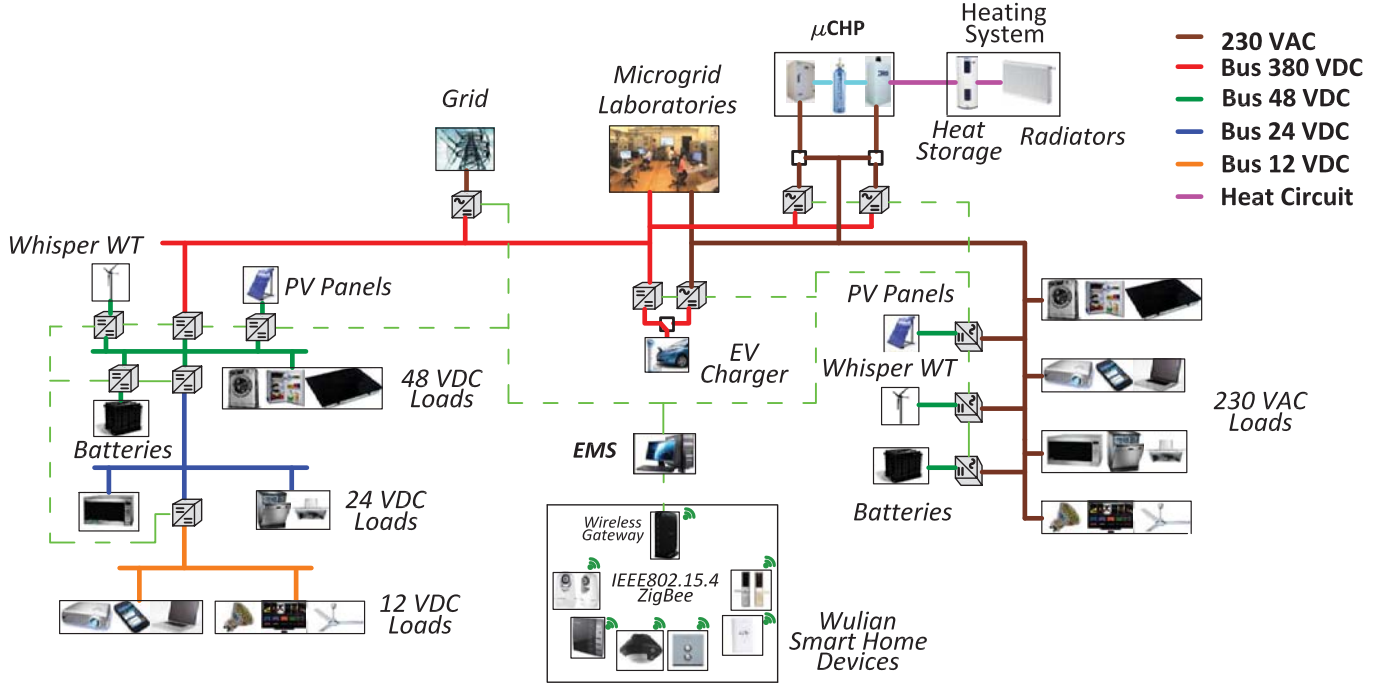


Fig. 3: Power Architecture of the Living Laboratory at Aalborg University.

B. Living Laboratory

The Living Laboratory will be strategically located for its interconnection with the Intelligent DC Microgrid Laboratory, and therefore being able to integrate the new demonstration facility into a bigger network if required. The Living Laboratory will be divided in two sections. Both sections are fully functional residential apartments. However, in one section a low voltage DC distribution system will be implemented, which is designed as a multi-bus system with voltages from 380 VDC to 12 VDC. The second section will use an ordinary 230 V 50 Hz distribution system. The designed power architecture of the facility is shown in Figure 3. Both sections will be able to work as independent microgrids, which will bring the opportunity to directly study and validate the potential energy savings of using a LVDC distribution system for residential applications.

The μ -CHP system shown in Fig 3 consists of an electrolyzer, a hydrogen storage, and a fuel cell. It produces electricity and heat, by combining hydrogen and air, with only one by-product, pure water. This feature is extremely important in Denmark, since the government aims for achieving a full renewable energy production by 2050. When there is an excess of solar and wind energy generation, the energy management system can decide whether to store the energy in the batteries or as hydrogen. This architecture perfectly lines up with the Danish Smart Grid Strategy, which is focused on the development and implementation of hydrogen-based technologies, in order to integrate the electricity grid with the gas grid and district heating grid, into a new smart energy system. The main purpose of the Danish strategy is to use the gas and district heating grid to store energy from the wind power generation when the electricity prices are low [13].

The Intelligent DC Microgrid Laboratory will be equipped with smart home devices. A wireless communication protocol, based on ZigBee, is used by the devices to send and receive the information. The main features offered by this system is a low bit rate, low energy consumption and low cost. All the devices communicate with the gateway device, which is the one sending the information to the energy management system, as shown in Fig 3.

OMNIA smart metering system [14] developed by Kamstrup will be installed as well. In several countries, especially Denmark, an efficient EMS cannot be limited to only manage the electrical grid, it should also include the heating systems when they are not electrical-based. The OMNIA smart metering system will allow the integration of smart metering devices for the electrical, gas and district heating grid, and therefore, allowing the EMS to have full-controllability of the building energy consumption.

It is expected that the Intelligent DC Microgrid Laboratory for residential applications, together with the future Living Laboratory will boost the research on this topic, especially in Europe, where in comparison with other regions, there is a lack of facilities for testing and implementation.

III. INTELLIGENT DC MICROGRID LABORATORY IN NCEPU FOR INDUSTRIAL APPLICATIONS

A living lab focused on DC microgrids for commercial buildings and industrial applications will be established in North China Electric Power University (NCEPU). Fig. 4 gives the electrical scheme of the living lab which consists of two 750V DC bus. PV generation system is connected to Bus 1 through DC/DC converter, load converters are used to support both AC (220V) and DC (110V) load. Within Bus 2, microgrid

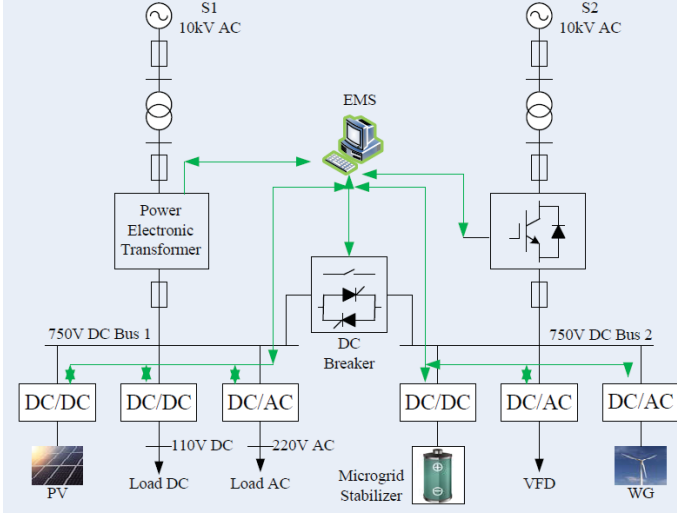


Fig. 4: Electrical scheme of Industrial DC Microgrid.

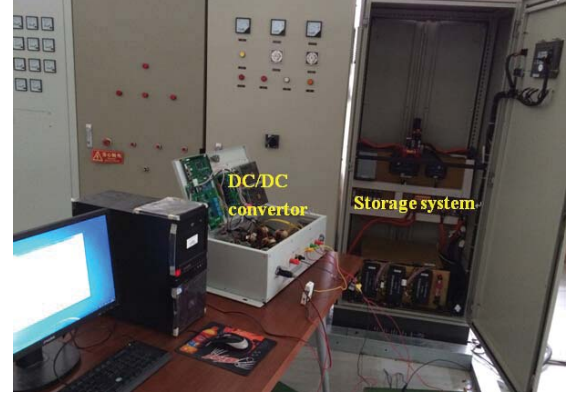
stabilizer, variable frequency drive (VFD) and wind power system are integrated. A DC breaker connects Bus 1 and Bus 2 together. Bus 1 connects to AC system (S1) through a power electronic transformer. A bidirectional pulse width-modulated (PWM) AC/DC voltage-source converter (VSC) is used to interface the Bus 2 to an AC system (S2). Energy management system (EMS) provides coordinated control method based on local information.

A. Microgrid Stabilizer

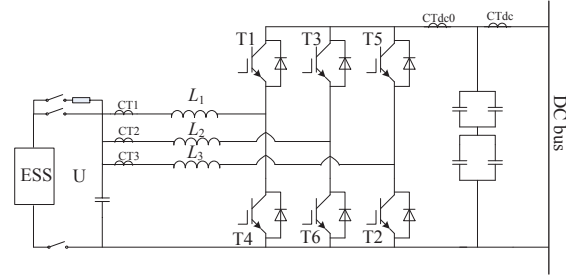
Microgrid stabilizer is developed based on energy storage system (ESS) and a DC/DC converter. It can flexibly import/export power from/to the microgrid. When the microgrid operates in grid-connected mode, the microgrid stabilizer can compensate the power variations or reduce the power fluctuations caused by the renewable energy sources which are characterized by having a stochastic and intermittent behavior. When microgrid is disconnected from the main grid, thus operating in islanded mode, it is necessary to use the microgrid stabilizer to balance power in the microgrid and regulate DC bus voltage. The experimental setup of microgrid stabilizer built by NCEPU is illustrated in Fig. 5a and its electrical scheme is shown in Fig. 5b.

The control system for the microgrid stabilizer is designed based on traditional PI (Proportional- Integral) controller. Figure 6 presents the experimental results of the microgrid stabilizer when a resistance load is connected to it. The storage system voltage u_{ESS} is 400V and the load side voltage u_{DC} is 750V. i_{L2} is current waveform of inductor L2, its average value is 0.135A. i_{ESS} is the output current waveform of ESS, its average value is 3.53A. All the waveforms kept stable during the whole period.

As microgrid sees an increasing number of renewable energy sources and load, the microgrid stabilizer must be robust against disturbances, having good voltage regulation and fast dynamic response. Therefore, in future works we will explore more control algorithms that can overcome the uncertainty, and to achieve better compensation and global stability



(a)



(b)

Fig. 5: a) Experimental Setup of the Microgrid Stabilizer, b) Electrical Scheme of the Microgrid Stabilizer.

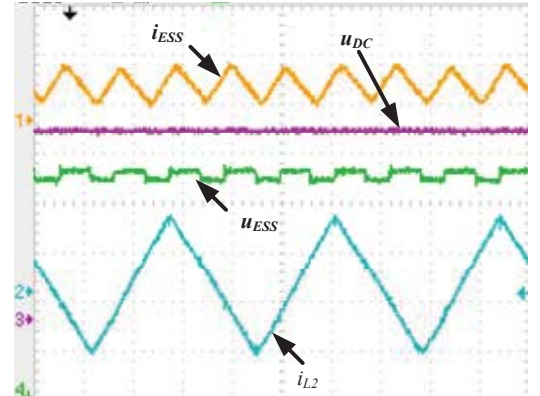


Fig. 6: Experimental results of Microgrid Stabilizer.

B. EMS and Coordinated Control

The research work of energy management and coordinated control of DC microgrid is undertaken by Institute of Electrical Engineering, Chinese Academy of Sciences (IEE-CAS). Zhang proposed an energy management and coordinated control method for low voltage DC microgrid based on local information [15]. A DC voltage coordinated control strategy is discussed in [16], which analysis the coordinated operation between the interface VSC and electric vehicle energy storage system under grid-connected operation, converter current-limit and islanding operation conditions. Pei proposed an adaptive



Fig. 7: Four-terminal DC-Grid Prototype in NCEPU.

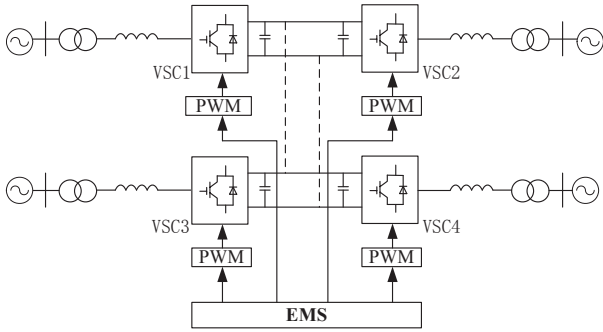


Fig. 8: Electrical Scheme of Four-terminal DC-Grid Prototype in NCEPU.

droop control for the multi-terminal low voltage DC distribution system, and presented a probabilistic evaluation method to analyze the plug-in electric vehicle integration capacity [17]. Based on these research work, IEE-CAS is going to design energy management system for the microgrid in Fig. 4 to integrate each element to the system, allowing fault protection, global stability, and optimal efficiency.

C. Testing Platform

The research outcomes, i.e. the robustness and reliability of the microgrid stabilizer, the feasibility of the EMS will be tested in different testing platforms. Fig. 7 shows four-terminal DC grid prototype in NCEPU, Fig. 8 gives its electrical scheme [18].

Fig. 9 presents electrical scheme of a 750V DC microgrid demonstration project built by IEE-CAS. PV generation and wind power generation are the major power source as shown in Fig. 10. There are nine groups of PV panel connected to the DC microgrid through a 10 kW DC/DC converter, which include mono-crystal, polycrystalline, amorphous, thin film solar cell. One 50 kW and two 10 kW wind generators are integrated into the DC microgrid. Fig. 11 shows the DC grid supervising system.

Based on the research work and testing results, a living lab focused on DC microgrids for commercial buildings and industrial applications will be established in China for research, demo and test of energy solutions for commercial buildings. It will boost the industrial applicability of DC microgrid.

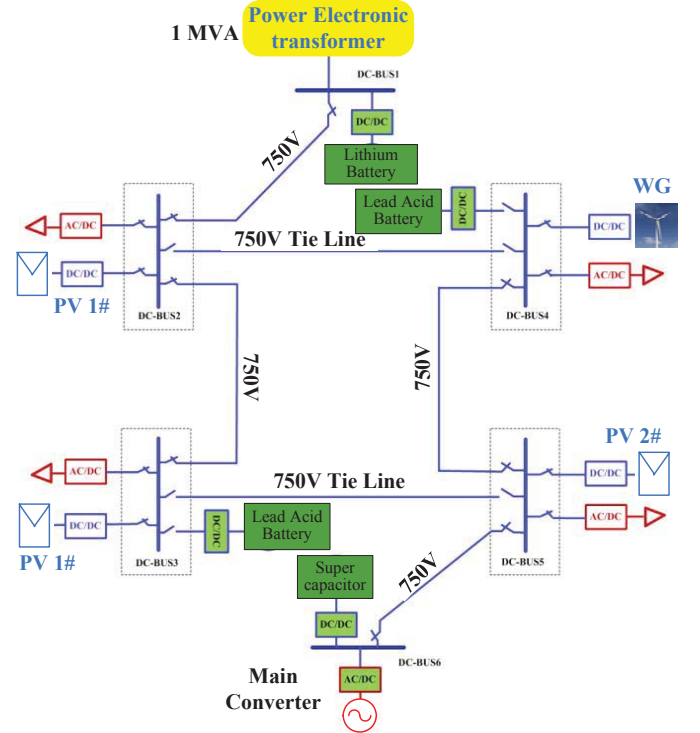


Fig. 9: DC Microgrid Demonstration Project Developed by CSA-IEE.



Fig. 10: Power Sources in DC Microgrid.

IV. CONCLUSIONS AND FUTURE WORKS

This paper has described the Intelligent DC Microgrid Laboratories developed for the research and implementation of future DC microgrids for both residential and industrial applications. These facilities are the outcome of the collaboration project between the two research institutes, North China Electric Power University and Aalborg University. The design, modelling, control, coordination, communication and management of DC microgrids will be explored using the new laboratories. Also, the potential advantages of integrating the electrical grid together with the gas grid and the district



Fig. 11: DC Grid Supervising System Developed by CSA-IEE.

heating grid, into one smart energy system, will be studied and analysed, especially in Denmark. In order to conclude, it is expected that the facilities boost the interest and research, from both public and private sectors, on this topic, in order to develop new products, control algorithms, architectures, and standards.

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