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Hardware-in-the-loop Emulation of a Control and Longitudinal Compensation System of a Submarine

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Abstract— *Naval machinery is designed to ensure proper operation of a ship and includes pumps, compressors, tanks, piping and other equipment. In modern vessels, the operation of this equipment is automated through Programmable Logic Controllers (PLC). In general, the development of PLC control software takes place in parallel with the mechanical construction of the vessels, so that integration tests are performed only at the time of commissioning. In order to reduce the risks associated with integration, the tests are performed by comparing the control software against a real-time simulator of the plant to be controlled. The contribution of this work is the development of a commissioning solution for the longitudinal compensation system of a submarine-based in a virtual simulation environment called Hardware-in-the-Loop (HIL). A HIL simulation refers to a system in which parts of a pure simulation have been replaced with actual physical components. The results were considered satisfactory since the test platform allowed the early identification of errors in the PLC software, tests of different control strategies and finally the possibility of the use for the purpose of operator training.*
Keywords— Virtual commissioning, programmable logic controllers, control system, submarine, Hardware-in-the-loop, simulation.

I. INTRODUCTION

The use of modeling and simulation software has become increasingly popular in offshore machinery design. This reduces the effort of project engineers by allowing them to test and remake various solutions in a virtual simulation environment. In addition, virtual prototyping indirectly helps reduce the number of accidents because critical or defective equipment components can be identified early in the project. This is a strong argument that supports the effort to create more realistic and reliable simulators for naval systems [1], [2], [3], [4].

In recent years, one of the most used techniques for prototyping and testing is called Hardware-in-the-Loop (HIL). According to the manufacturer of National Instruments, HIL is a method that offers powerful features and greater efficiency to the test of embedded systems, since it allows to simulate the subsystems that cannot be physically included in the tests, which allows validating the control completely in a virtual environment before moving on to the whole system tests in the real world. A significant role of the HIL real-time simulation platform is to test the software of controllers under normal or abnormal conditions, so as to verify the corresponding response expected [5], [6], [7], [8]. Figure 1 exemplifies the concept of implementing a system for HIL tests.

Many authors have considered the HIL in a naval system. For instance, Sanchez et al [9] presented the ability of HIL models to emulate a diesel engine generator in a US Navy ship. Modifications to a previously documented experiment have been made to replace a gasoline-powered generator with a HIL diesel generator and it has been shown that when the generator is used alone to power a transient load, the power quality is severely impacted.

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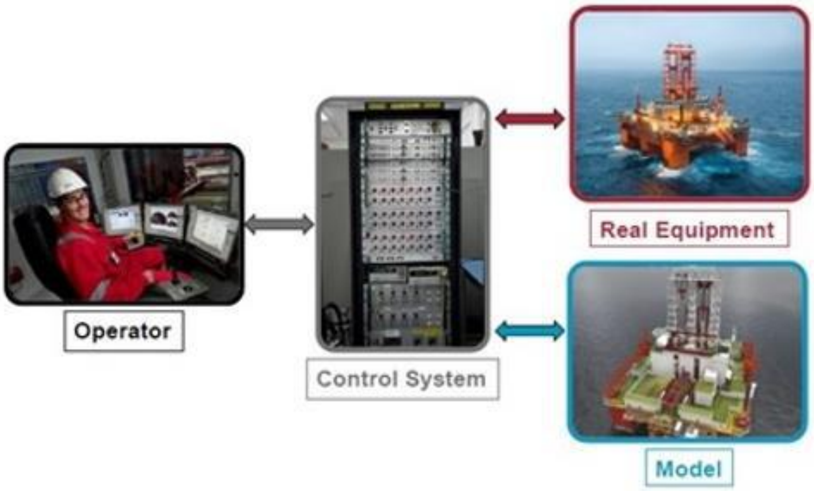

Fig. 1.Hardware-in-the-Loop concept [6].

Nounou et al [10] present a Hardware-in-the-Loop Emulation of an Electric Naval Propulsion System based on a Multiphase Permanent Magnet Synchronous Machine. The emulator of the Electric Naval Propulsion System was used to emulate the effect of propeller resistive torque on the propulsion motor. Dufour et al [11] describe a HIL test made on a simplified zonal power system of a naval ship. This approach is compatible with model-based design; a design philosophy that is based entirely on simulation models, from the specifications to release and field commissioning. Palla et al [12] present a design procedure of HIL test for power system modeling and simulation using Simulink and National Instruments (NI) equipment. The validated relay model can be used in the modeling of Shipboard Power Systems (SPS).

Ji-qing et al [13] present a fuzzy control method based on the varied universe to determine the overall control system structure and the corresponding parameters. This approach not only improves the accuracy of the control system but also makes the control object enjoy a certain anti-interference ability.

In this paper, the development of a commissioning solution for the longitudinal compensation system of a submarine has been presented. A virtual simulation environment called Hardware-in-the-Loop (HIL) was built up with the LabVIEW Control Design, Programmable Logic Controller (PLC) and Control System (SCADA) .

This paper is organized as follows: Section 1 gives the general introduction of the topic. Section 2 gives a brief description of the virtual commissioning platform. Section 3 presents the experiments and analysis while section 4 provides the results and conclusion.

II. THEORETICAL BACKGROUND

A. Longitudinal Compensation System – TRIM System

Submarines are very sensitive to weight displacement, and during their operation, the center of gravity may be affected due to the withdrawal of loads such as fuel consumption and unloading of weapons. To ensure stability and good navigability, the submarine must maintain the balance between the front and rear [13]. This project studied a system of adjustment and compensation of the longitudinal weight of a submarine, better known as the TRIM system[14], [15]. TRIM is particularly sensitive on a submarine once submerged due to the lack of a waterline. The TRIM movement of the underwater vehicle is controlled by adjusting the volume of ballast water in the bow and stern ballast tanks [13]. The system consists basically of two water tanks, connected in a closed circuit, located aft and ahead of the submarine, being the longitudinal adjustment obtained from the movement of water between the two tanks, as can be seen in Figure 2.

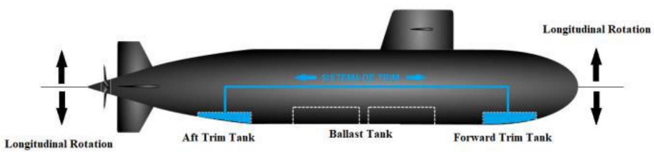

Fig. 2. TRIM adjustment system.

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According to the variation of the level in the tanks (figure 2), the submarine revolves around its horizontal axis. It is also possible to simulate external factors that may affect the angle of the submarine. These factors are represented by two controls. The first is the weight of the longitudinal displacement moment (w) and the second is the arm of the longitudinal displacement moment (l). In this way, the operator can simulate where external situations affect the TRIM angle of the submarine and verify the behaviour of the control system in the occurrence of these external disturbances. Equation (1) determines the TRIM angle of the submarine [16].

$$\tan\theta = \frac{wl}{\Delta_s \overline{BG_0}} \quad (1)$$

Where:

w = weight of the longitudinal displacement moment;

l = longitudinal moment arm;

Δ_s = submarine weight;

$\overline{BG_0}$ = distance between the center of gravity and the center of fluctuation;

θ = angle of TRIM of the submarine.

B. Hardware Components – HIL System

HIL testing is a technique where real signals from a controller are connected to a test system that simulates reality, tricking the controller into thinking it is in the assembled product. Test and design iteration takes place as though the real-world system is being used. HIL systems can vary considerably from application to application. Even so, it is possible to identify numerous components that are always present in a similar form[8]. Hardware components of HIL system are: (i) Host PC; (ii) Real-time processor system; (iii) I/O boards and signal conditioning system (PLC); (iv) Bus system; (v) Electrical loads and local simulation; (vi) Electrical fault simulation and; (vii) Real components. Figure 3 presents the components of a HIL system.

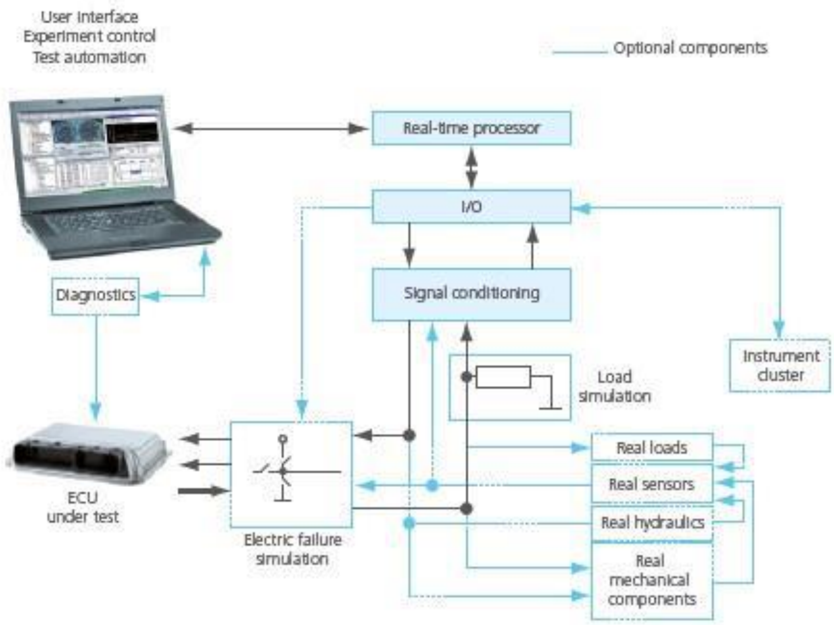

Fig. 3.Components of a HIL system [8].

III. VIRTUAL COMMISSIONING PLATFORM

The virtual commissioning and test platform HIL developed in this work (Fig. 4) used two computers connected through an Ethernet switch and RJ-45 cables, creating a local network. In the first computer was used the SCADA software TIA Portal manufactured by Siemens . The choice of this tool was because it is a fully integrated engineering platform for the development of industrial automation solutions. In the same environment, the programming of the PLC was developed according to the languages and specifications defined in the standard IEC 61311-3.

In the second computer, were simulated the equipment of a longitudinal compensation system of the submarine. This simulator was developed using LabVIEW software developed by National Instruments. This software allows the implementation of systems and tests in real-time, with user-friendly interface and features such as graphing and reporting. From the point of view of the control system, the simulation environment had the same behaviour as a real system, and no differences in interacting with simulated equipment or physically existing equipment. The response dynamics of the simulated equipment, as well as the generated signals, were the same as those of a real system. The virtual commissioning and test platform HIL developed in this work are presented in Figure 4.

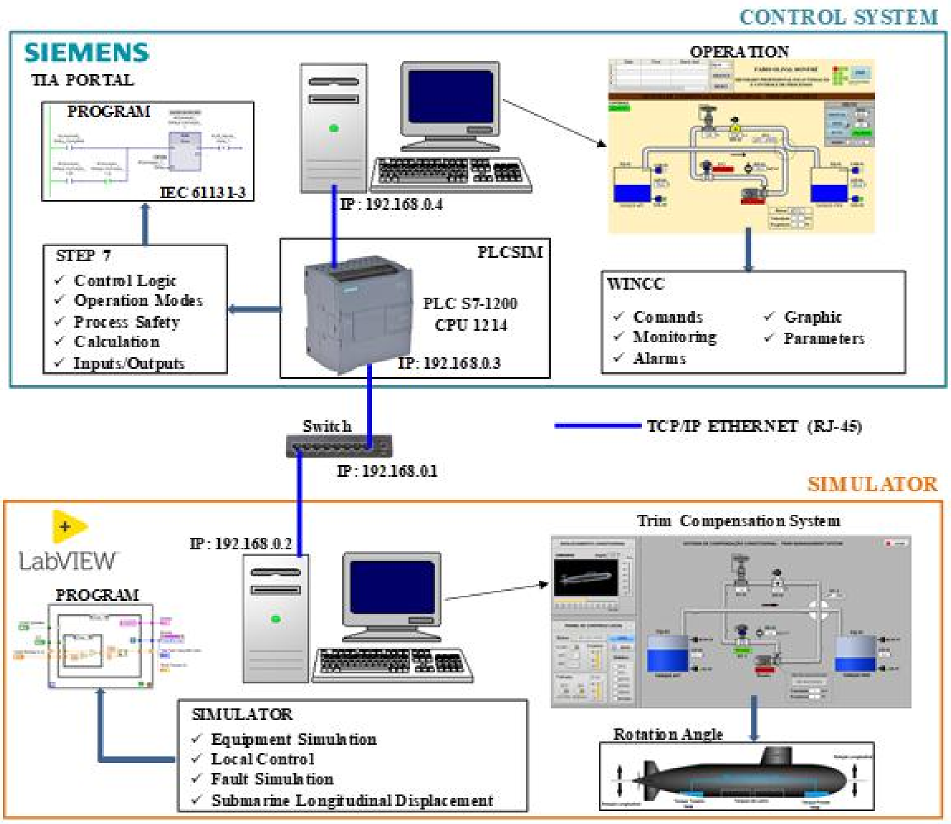

Fig. 4. The virtual commissioning and test platform HIL.

C. Longitudinal Compensation System

Figure 5 shows the front panel of the longitudinal compensation system simulator. It consists of two tanks with a capacity of 100 liters capable of moving the TRIM angle of the submarine by 30º. In order to carry out the transfer between the tanks, a motor / pump assembly was used that could be operated by different methods (direct start, soft starter and frequency inverter), plus a 4-way valve with two positions for reversing the flow sense of water flow between the tanks. The system also- had level sensors in the tanks, water pressure flow line pressure sensor. There was also an interface with the operator that allows insertion of faults in the equipment for the installation.

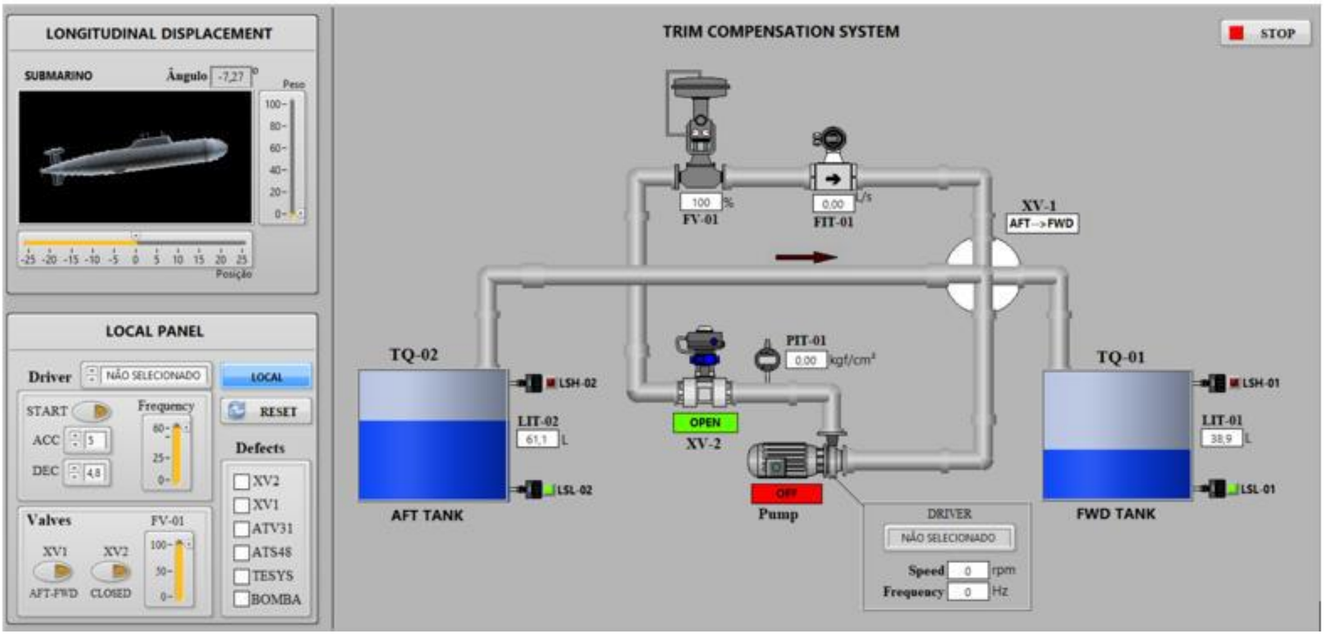

Fig. 5.The front panel of the longitudinal compensation system simulator

This feature is a great advantage of the use of a virtual commissioning platform because through the simulator programming defects were added in the equipment, which was used to verify the behaviour of the control system in such situations. In the case of the developed simulator, it was enough that the operator clicked on one of the selection buttons on the defect menu to add a fault during the simulation.

D. Control System (SCADA)

Figure 6 presents a front panel of the Control System (SCADA).

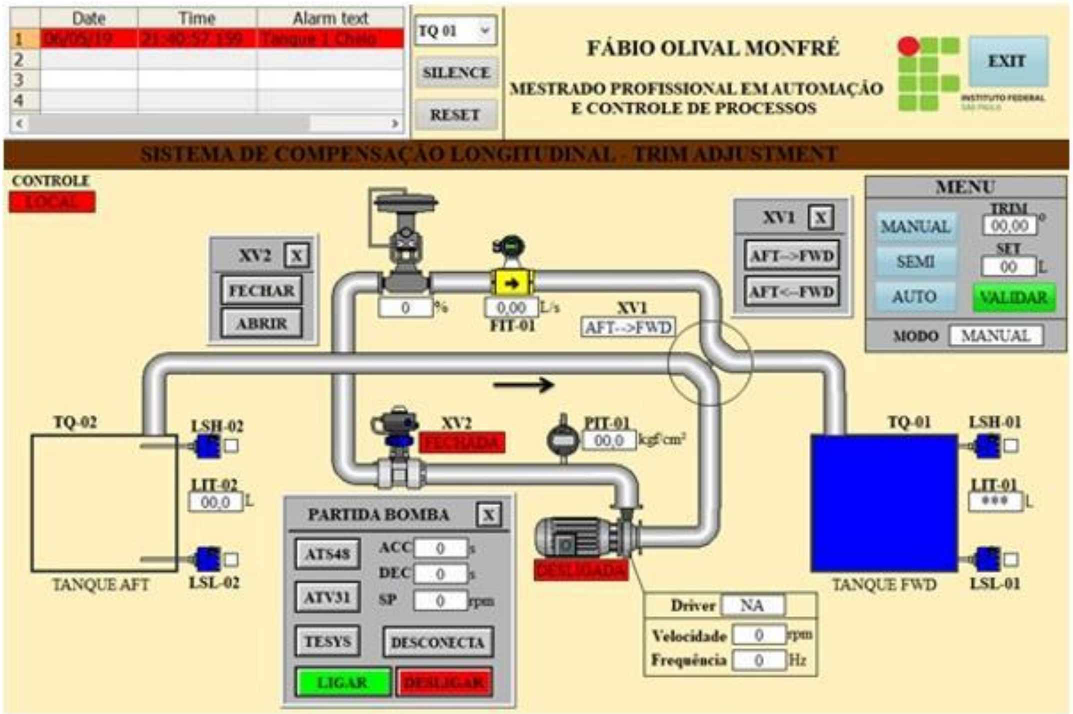

Fig. 6.The front panel of the control system (SCADA).

The front panel of the control system allows three control modes:

- **Manual / Configuration**: In this mode, all the equipment is manually controlled by the operator through the Human Machine Interface (HMI)

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screen, as well as the configuration of the parameters of the equipment such as starting methods, speed and ramp time.

- **Semi-Automatic**: In this control mode the operator must choose the amount of water to be transferred between the tanks taking into account the parameterization of the equipment performance in the manual / configuration mode, such as the water transfer direction adjustment of the valve (XV -1).
- **Automatic**: This control mode takes the submarine to the TRIM angle automatically. The program developed in the PLC reads the current TRIM angle and does all the necessary sequencing, also using a proportional control for the pump speed set-point, as seen in Fig. 7.

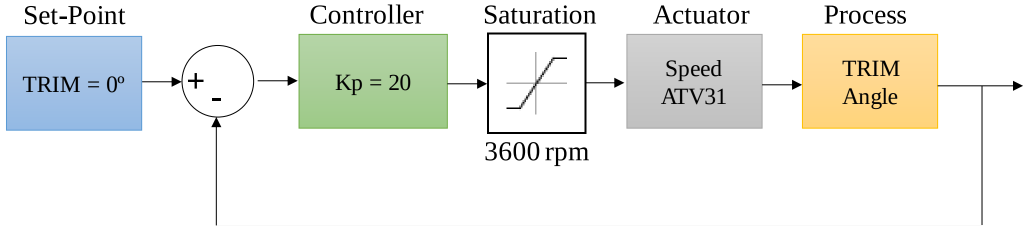

Fig. 7.The control diagram of the pump speed set-point.

IV. EXPERIMENTS AND ANALYSIS

To implement the system performance tests, the SCADA software graph tool was used, generating real-time values of the system. The purpose of these tests was to observe whether the control system effectively takes the submarine to TRIM zero position automatically and independently of external disturbance conditions. For this, three variables were measured: TQ-02 level, TRIM angle, and Pump speed. The initial TRIM angle for the test was -10º. It was observed that as soon as the operator passed the control system to the manual mode, the speed of the motor was maximized, saturating at 3600 rpm. This happened because the error between the angle set-point ~~is~~ was the actual angle which was too great, causing the controller to send a very high-speed value to the pump. As the angle approached zero, the speed of the pump decreased proportionally. As a result, it was observed that the zero TRIM angle was perfectly achieved, as can be seen in Figure 8. It was further noted that since the submarine had no disturbance external to the compensation system the volume value of the TQ-02 and TQ-01 ~~is~~ was exactly 50 litres.

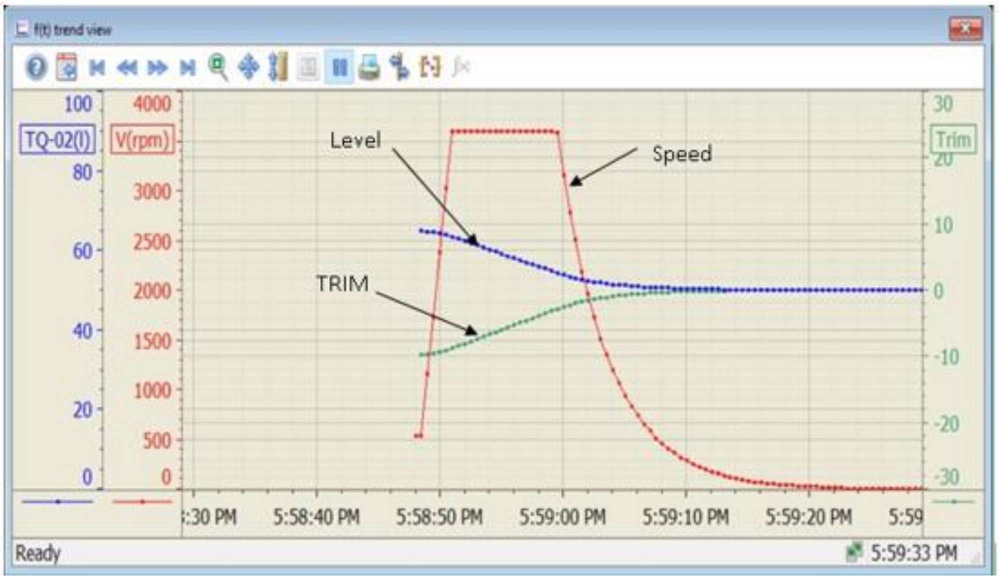

Fig. 8.Performance automatic mode – balanced submarine.

A second test was performed in automatic mode, but this time with the submarine unbalanced. From this weight change, a longitudinal unbalance occurred, resulting in a non-zero TRIM angle. The simulation of this external disturbance was performed by adjusting the weight and position of the controls of the longitudinal compensation system. The control system made the transfer of water between the tanks, taking the submarine from an angle of approximately -20º to the ideal setting of zero degrees, as can be seen in Figure 9. It ~~is~~ was also verified that due to the longitudinal unbalance initial value of the submarine, the value at TQ-02 at the end of the transfer cycle was different from 50 liters, proving that the control system was capable of bringing the submarine to the TRIM angle equal to zero under different conditions.

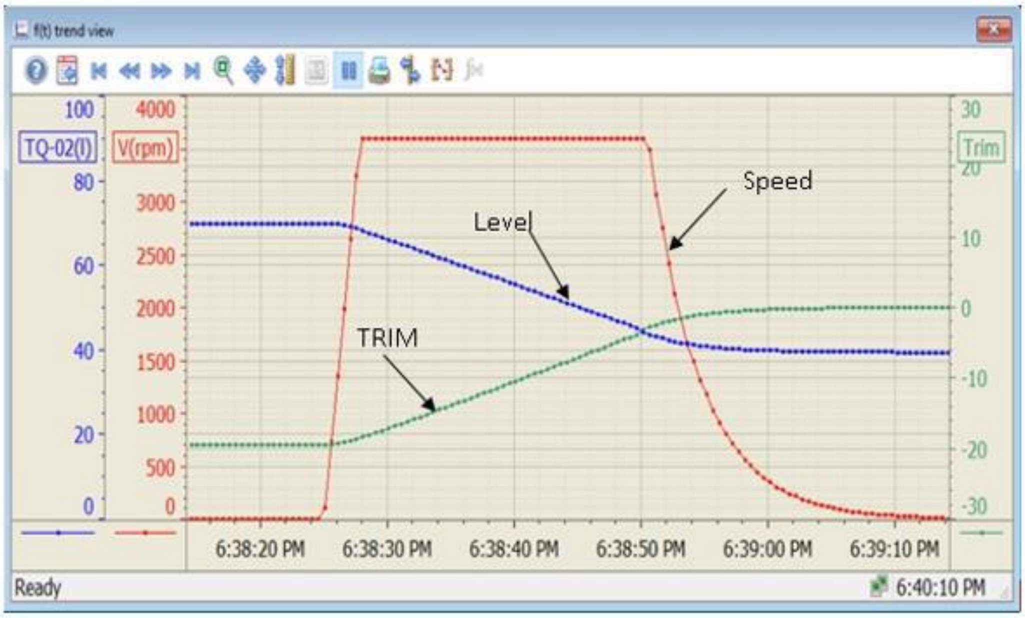

Fig. 9.Performance automatic mode – unbalanced submarine

V. RESULTS AND CONCLUSIONS

The main goal of this paper was to explain various testing requirements needed for the development of a commissioning solution for the longitudinal compensation system of a submarine. In this paper, an emulation of control and longitudinal compensation system of a submarine using the technique of Hardware-in-the-Loop (HIL) was carried out. From simulation and experimental results, it could be concluded that the emulator could reproduce the dynamic of the longitudinal compensation system, and the control was well done. The presented emulator could be useful for repetitive tests that were required for commissioning of a submarine. The results were considered satisfactory since the test platform allowed the early identification of errors in the PLC software, tests of different control strategies and finally the possibility of the use for the purpose of operator training.

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