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A novel ventilation control strategy with piston effect for optimal management in a subway station

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Abstract

In this paper, we develop a novel approach for electrical daily management of subway station ventilation applied to a microgrid. Piston effect caused by the train air pressure is modelled. It is integrated into the control strategy in order to improve the motor speed's dynamic characteristics. The air flow control is emulated on a laboratory experimental test bench.

The main purpose of the paper is the speed control of the ventilation by considering different external data (Air quality, temperature…) and without reducing the equipment lifetime. For achieving it, two control strategies are necessary: High-level control and Low-level control.
The high-level control is an airflow input control considering external data, this input is converted into rotational speed according to the fan characteristics. The motor speed is controlled in function of this input.

The low-level control takes back the high level-control in order to improve the motor dynamics for high frequency.

A piston effect, due to the forced-air flow inside a tunnel or shaft caused by moving trains, disturbs the ventilation control. The piston effect is seen like a resistive torque by the system and is taken into account in the high-level control strategy. The air flow control dynamic is reproduced on a laboratory test bench at reduced scale.

Keywords: subway stations; piston effect; motor speed dynamic; PMSM; high level control; low level control;

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1. Introduction

In the frame of collaborative research coordinated by Efficacity Institute, a private-public partnership including IFSTTAR, a public transportation operator, and energy companies, consist in reducing the energy consumption in urban subway station, considering the passenger comfort (like the air-quality). The main challenge is to improve the existing material with new operating mode and limited intrusive actions without any influence on the current maintenance operations. A station electrical consumption investigation made in Paris metro has shown that almost the half of stations consumers are motors (ventilation, escalators, lifts, pumps etc…). The study concerns all systems impacted by a load torque like ventilation impacted by the piston effect.

Nowadays, in subway station, the ventilation is not optimized regarding to the electrical consumption. High level control strategies already exist in order to give the daily optimal working profiles (DAO) with the energy consumption minimization objective referenced by Rigault *et al.* (2016). The constraints in this system are the Indoor Air Quality (IAQ), the Outdoor Air Quality (OAQ), the fine particles created by the train movement with an equivalent Air Quality constraint. However, this control strategy does not take into account the dynamic behavior linked to the piston effect. Some equipment is stressed by the piston effect likes ventilation. The optimal reference cannot manage fast transient in order not to reduce lifetime motor equipment. This fast control strategy we propose should be reused in all kinds of stations motors systems stressed by a load torque. In this study, we focus on the synchronous motor. The field-oriented control is adopted for the motor regulation referenced by Pradeep K. Nandeem *et al.* (1987) and by Faa-Jeng Lin (1997). It permits to manage transient effects and regulate the various system parameters according to an optimal reference referenced by M.B. Daigavane *et al.* (2016).

The paper details the piston effect and its representation as a resistive torque for the ventilation system. The model of the global motor ventilation system is built using Matlab/Simulink©. The physical parameters of the piston effect (air flow, pressure…) are converted in order to be adapted for the electrical simulation. Simulation results show the system energy consumption with an operating mode integrating two control levels. The motor-ventilation electrical system is emulated at a reduced scale on a test bench in laboratory, and first experimental results for the emulated airflow management are performed.

2. System simulation

2.1. Piston effect

Piston effect is due to the forced-air flow inside a tunnel or shaft caused by moving trains. The pressure difference formed by the moving air around and behind the train lifts fine particles.

The distributions of flow velocities inside the tunnel induced by moving vehicles weakly depend upon the vehicle speed, vehicle spacing and vehicle size. T.Y. Chen *et al.* (1998) shows that the piston effect in the upper region of the tunnel is 40% of that around vehicle.

The pollutant air inside the tunnel is discharged using a mechanical ventilation shafts to provide a suitable environment for passengers referenced by Kyung Jin Ryu *et al.* (2012). The mechanical ventilation sees the piston effect as a load torque.

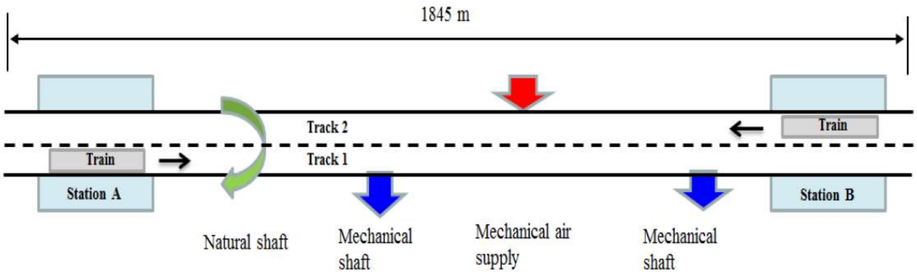

Fig. 1 Schematic view of the existing subway tunnel referenced by Kyung Jin Ryu *et al.* (2012)

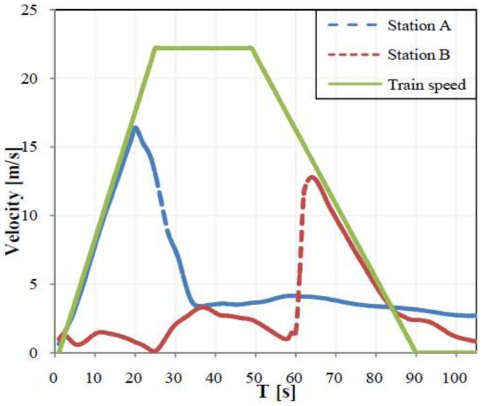

Fig. 2 Temporal variation of velocity at the station A and B with the train speed referenced by Kyung Jin Ryu *et al.* (2012)

Today in stations the piston effect is used to generate a natural ventilation. The discharged airflow through the exit of the shaft increases as the train approaches the shaft. High velocity occurs at the exits of the mechanical ventilation shaft due to piston effect. Fig. 2 shows temporal variation of average velocity at the stations A and B due to the piston-effect. The airflow velocity behind the train increases as the train accelerates and decreases rapidly as the train runs with constant speed in the station A. The airflow velocity at the station B increases after the train decelerates and approaches to the station B. During this moment, the system is shut down and the pressure is used to rotating the ventilation system. With this solution, any control over the energy consumption and the system are required.

For the study, the pressure inside station A has been chosen as a set point which is considered as the most constraining for the studied ventilation system. This approach does not need the overall description of the station area, tunnel volume and train characteristics.

2.2. Ventilation model

The vector control of a synchronous motor consists in keeping constant or slowly varies the angular offset between back-e.m.f (electromotive forces) and stator currents (cf. Figure 3). With this condition, the electromagnetic torque developed by the motor can be controlled and a speed or position control loop can be designed around the control loop of the torque of the machine. To realize this task, the machine must be controlled by a position sensor connected to the rotor. This allows the current or voltage to ensure the control of the maximal torque of the machine. Generally speaking, permanent magnet synchronous machine supplied by current controlled voltage inverter, operates in sinusoidal or rectangular mode. The choice of a supply mode is based on technical, economical criteria, criteria of performance and operating safety. The current controlled voltage source for the inverter topology has been adopted referenced by Al Kassem Jebai (2013).

The permanent magnet synchronous machine (PMSM) has a rotor with 5 pairs of poles (Table. 1). Permanents magnets create the rotor excitation. To simplify the model referenced by A. Kolli (2013), following assumptions have been made: there is no saliency effect, the rotor is smooth pole (constant air gap), the machine operating linearly (no saturation effect is taken into account), the motor phases are shifted by an angle of 2π/3.

Table 1. PMSM parameters

Parameters	Values
M_0 : Standstill torque (thermal continuous torque at low speeds)	27,5 Nm
I_0 : Standstill current	37,6 A
M_{pk} : Dynamic limit torque	107 Nm
I_{max} : Maximum permitted motor current	215 A
P : Number of pole pairs	5
J_{mot} : Mass moment of inertia of the brake motor	$18{,}1.10^{-4}$ kg.m^2
L_1 : Inductivity between connection and star point	0.84 mH
R_1 : Resistance between connection and star point	0,051 Ω

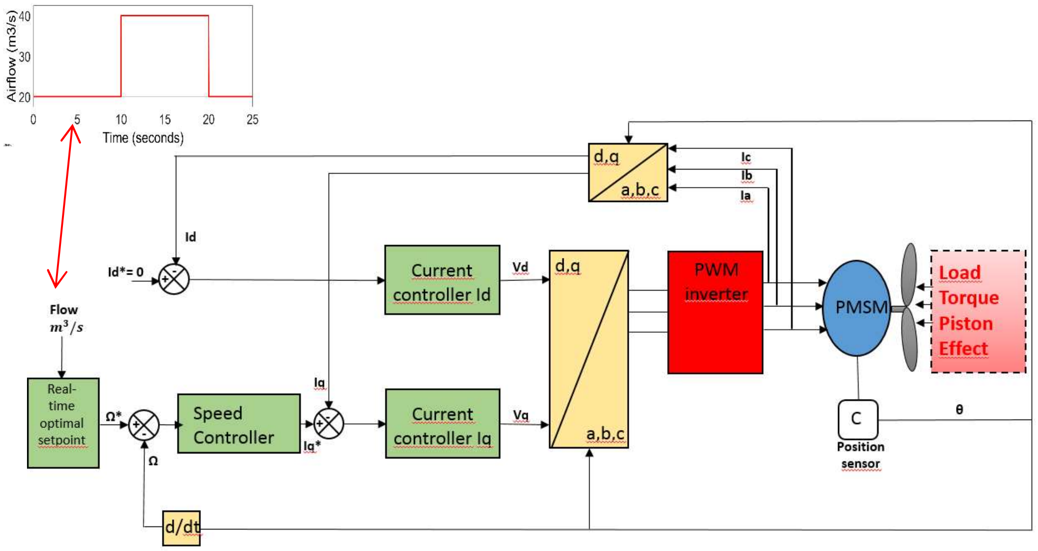

Fig. 3 Control command synopsis of the PMSM drive system for ventilation based on the vector control strategy

The system is speed controlled$(rad.s^{-1})$, the set point is given in flow $(m^3.s^{-1})$. Conversion of the flow into speed must be made. For that, the equation below is a solution referenced by L. Galaï-Dol *et al.* (2016):

$$P(W)=Q(m.s).Hm(Pa) \tag{1}$$

$$P(W)=Q(m.s).[Pstat+Pdyn](Pa) \tag{2}$$

$$Q(m.s)=\frac{\Omega(rad.s).T(N.m)}{[Pstat+Pdyn](Pa)} \tag{3}$$

Figures below are extracted from usual subway ventilations datasheet.

We can see in Fig. 4 and Fig. 5 that higher the airflow is, lower the dynamic and static pressure are but higher the mechanical torque (without piston effect) is. Hence a trade-off has to be established. The setpoint variation imposed in the simulation code is between 25m^3/s (best pressure compromise) and 40m^3/s usually used today in the underground station.

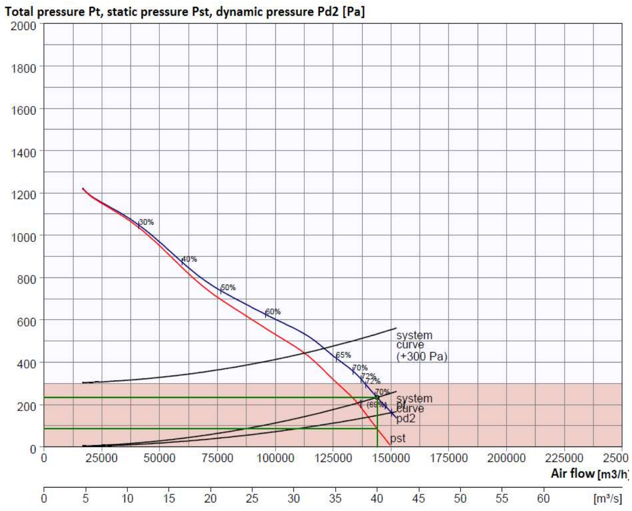

Fig. 4 Dynamic and static pressure in function of air flow

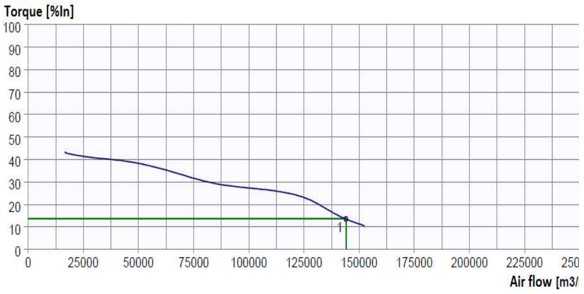

Fig. 5 Mechanical torque in function of air flow

2.3. Simulation results

Simulations have been performed in order to evaluate the different power and energy consumptions for 4 identified cases given by the high-level control:

- For an airflow of 25m^3/s with a piston effect
- For an airflow of 40m^3/s with a piston effect
- For an airflow of 25m^3/s without a piston effect
- For an airflow of 40m^3/s without a piston effect

The hypotheses are: input voltage level = 550V, piston effect maximal torque 15N.m at 15s, mechanical torque of ventilation depending on the airflow level (cf. Fig. 5).

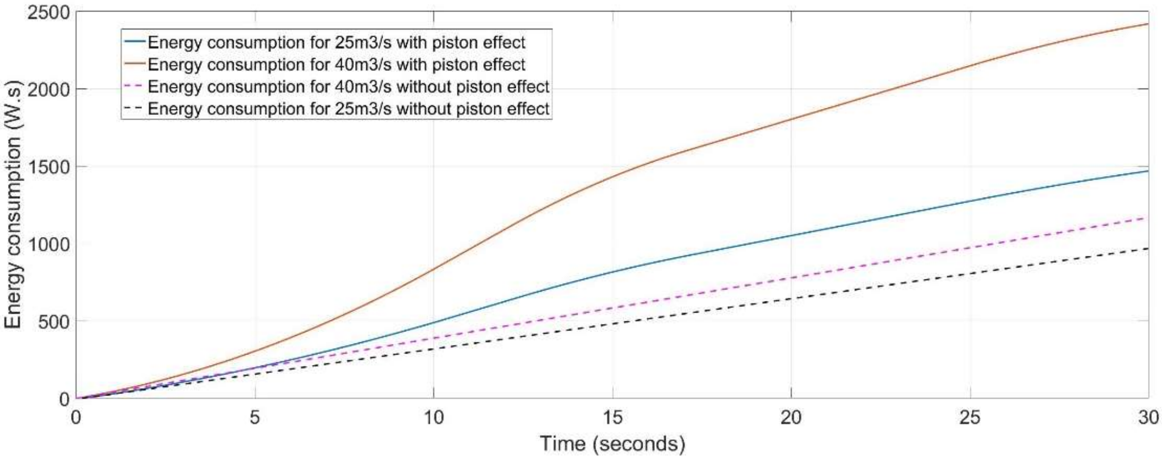

Fig. 6 Energy consumption comparison

In Fig.6 energy consumption for the 4 cases is represented for a 30 s duration. For cases without piston effect, it can be seen a linear evolution (dashed lines). At 25m^3/s airflow, the energy consumption is lower than 40m^3/s set point. For the cases with piston effect, it can be observed a slope change for the maximum resistive torque value. The energy consumption is higher for a 40m^3/s airflow than 25m^3/s. Energies values are summarized in table 2 for the daily consumption study including all these variations.

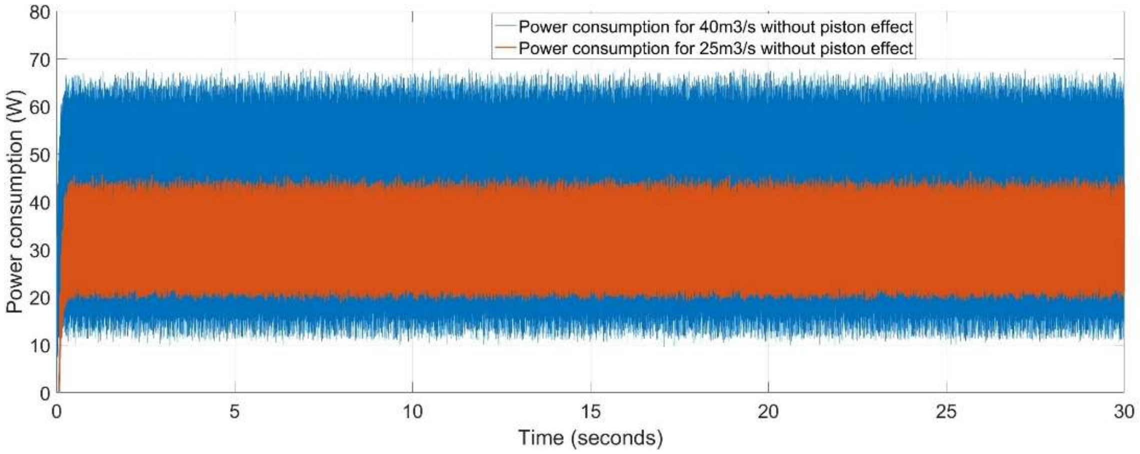

Fig. 7 Power demand comparison without piston effect

In Fig.7 power demand for two cases without piston effect is represented for a 30s duration. The ripple on the power consumption is due to the high frequency switching of the power converter semiconductors. It can be seen that the average power is continuous and that it is higher for a 40m^3/s setpoint.

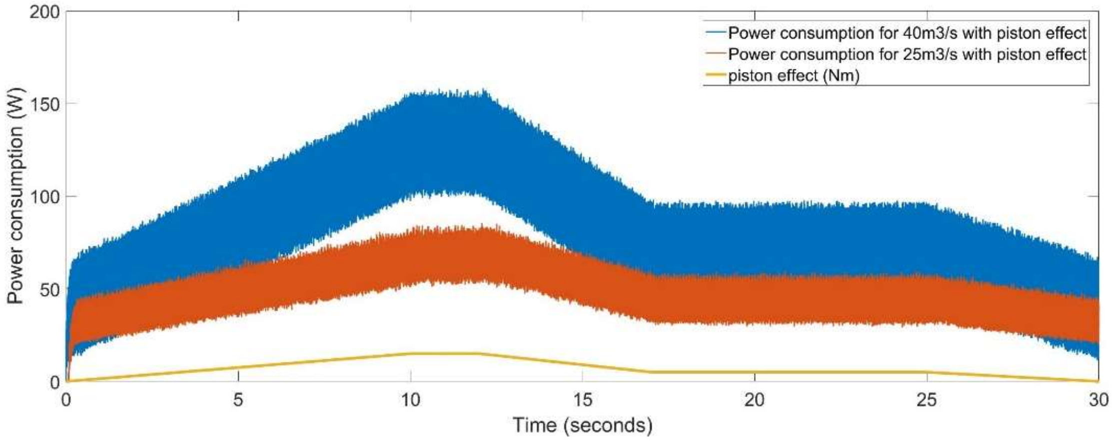

Fig. 8 Power demand comparison with piston effect

In Fig.8 power demand for two cases with piston effect is represented for a 30s duration. It can be seen that the power consumption follows the piston effect evolution (Fig. 8, yellow curve) and that it is higher for a 40m^3/s airflow. Simulation results demonstrate that it would be more appropriated to reduce the airflow for the energy consumption reduction, but the environmental undergrounds aspects lead to choose the highest airflow in order to provide the best comfort for subway's passengers (like particles matters evacuation). A trade-off is hence necessary, managed thanks to a long scale control over a whole day operation.

3. Experimentation

3.1. Experimental test bench

In this part, the procedures used for experimental motor control law implementation have been defined. Experimental issues of position recovery, current measurement and controller real time constraints have been also implemented on test bench. The considered electric drive is composed of two main parts: a power stage and a control stage which is mainly composed of a processor card DS1006 from *dSPACE*. Using the reference speed provided by the user and the measured stator currents, the processor controls the power stage to generate the voltage amplitude needed to control the PMSM at desired speed. The motor voltages are generated by the power stage using pulse width modulation technique (PWM) with F.P.G.A. card DS5202 AC MOTOR CONTROL.

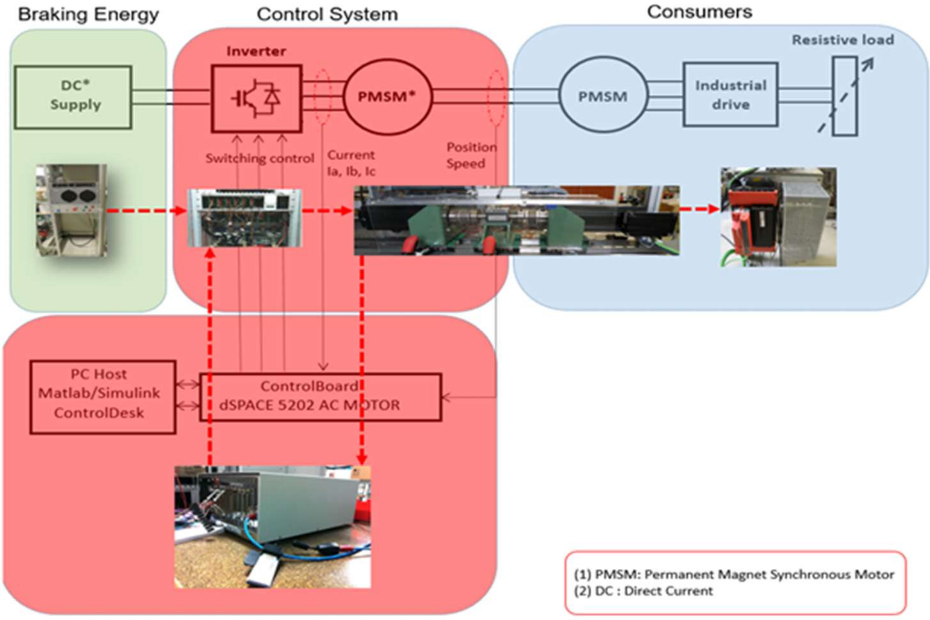

Fig. 9 Experimental test bench

The resistive load, the second PMSM and the inverter reproduce the behavior of the piston effect and the ventilation friction. A control law has been implemented for the inverter in order to achieve the same load torque.

3.2. Simulation validation

The validation of the simulation has been performed for a 550V DC input voltage, for two speed setpoints (150 rpm and 75 rpm) linked to the air flow control (40 m^3/s and 25 m^3/s). A comparison is made in Figure 10:

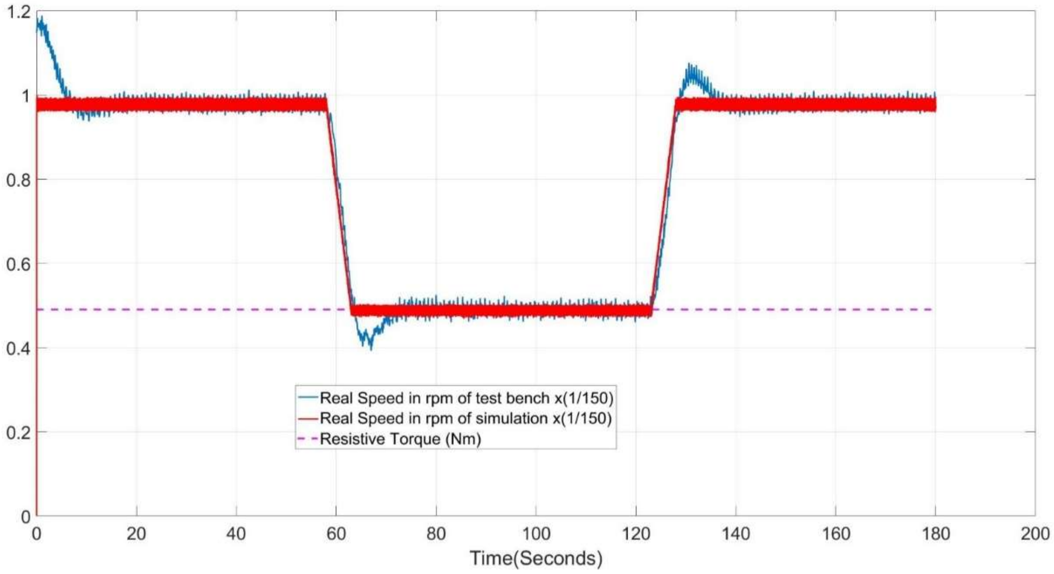

Fig. 10 Real speed comparison between test bench and simulation

The corrector implemented in the hardware control system quickly cancels the speed overshoot thanks to the performance of the controller (5% overshoot). It can be hence concluded that the experimentation is in good agreement with the simulation and validate the control principle.

The proposed control strategy presents an advantage in the case of a subway station ventilation study. Indeed, the overshoot generated by the piston effect leading to power losses, is controlled and minimized thanks to the control action. In addition, the mechanical stress on the ventilation system is reduced and the global efficiency of the system without disturbance of users' comfort is improved.

4. Use case: a subway station ventilation at reduced scale

In this use case, we study the daily consumption of a subway station ventilation with and without high level speed control. Usually, the ventilation set point is all day long at the maximum and at the minimum between 2 am and 5 am. Thanks to the high-level control, it is possible to optimize the energy consumption taking into account the environmental constraints referenced by Wenjie Chen *et al.* (2014) and by Kyung-Ran Lee *et al.* (2015). In order to estimate the whole consumption a simulation of all potential cases was made for 30s duration:

Table 2. Energy consumption for different use cases

Speed set point	Piston effect torque	Energy for 30s
0s to 15s: 150 rpm 15s to 30s: 75 rpm	No	3631 W
75 rpm	No	1468 W
75 rpm	Yes	2418 W
150 rpm	No	1166 W
150rpm	Yes	968 W

Usually, the airflow setpoint is the highest one all day long (45 m^3/s). The high-level control gives an optimal strategy for a daily scenario with data for 24h duration and a two minutes step. The optimal energy consumption (E opt in Fig. 11) was calculated with these setpoints (between 25 and 45 m^3/s). The usual energy consumption (E init) was calculated using the maximum airflow value.

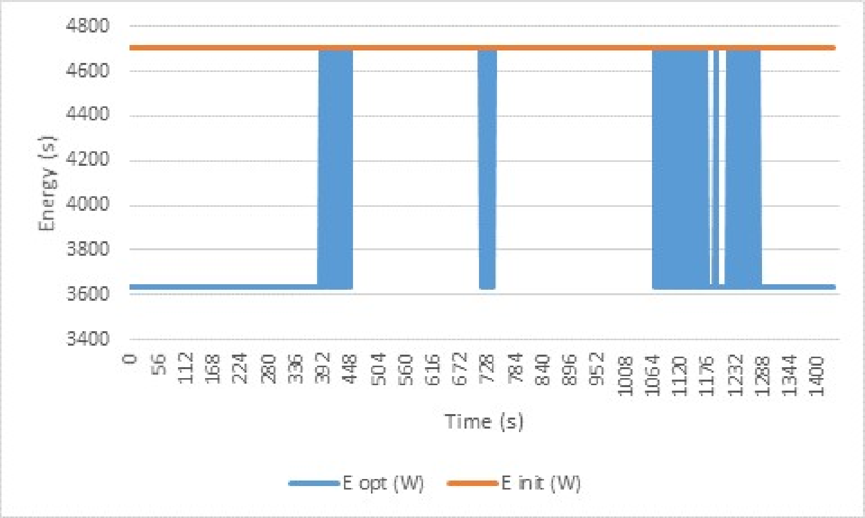

Fig. 11 Daily ventilation consumption with and without optimisation

Based on the experiment, the comparison between the usual case with a none speed variation and the optimal one given by the high-level control, highlights an energy gain of 11%.

5. Conclusion

In this paper, we proposed a novel ventilation control strategy taking into account piston effect for an optimal management of subway station. The study was first based on simulation, the airflow control was emulated and validated on a testbench at reduced scale. Energetic gain is about 11 % between usual ventilation operating mode compared to the optimal system proposed by a high-level management. Moreover, the adopted regulation permits to manage the overshoot in order to minimize the mechanical stress on the ventilation system and improve the efficiency.

If the recovered energy allows reducing the power production stemming from a coal-fired power plant, the annual CO2 emission gain would be almost 0.9 ton.

The solution described in this paper enables an optimization of the daily consumption with a variation of the set point at 2 minutes step. It should be interesting to implement the optimization strategy between the high level and the low-level control, taking into account the intermediate step for the grid voltage stability control. Such perspective should permit the integration of this controlled system into a microgrid structure.

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