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BEST PRACTICE FOR SELECTION OF FAN- AND DRIVE TECHNOLOGY IN TUNNEL VENTILATION APPLICATIONS

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ABSTRACT

When designing and defining the ventilation systems of road tunnels and safety tunnels, the question of possible combinations of fan and drive technologies and their evaluation regarding technical realisation and economic efficiency very often arises. A well-founded decision-making process for the selection of suitable combinations is only partially available and therefore, selection is often based on personal experience and preferences.

The FEDRO research project AGT 2015/005 addresses this issue by presenting the relevant fundamentals such as an overview of typical fan and drive technologies, the aerodynamic al requirements issued by the Swiss design codes as well as grid-compatibility requirements. The start-up currents as well as the harmonics related to the most common drive technologies are determined for typical ventilation applications by means of on-site tests.

Based on these fundamentals, aerodynamic and electric selection processes are developed, allowing to determine the suitable combinations of fan- and drive technology for a specific project. The aerodynamic selection process assesses e.g., the need for multiple operating points for an axial fan or the impact on longitudinal airspeed. The grid compatibility assessment analyses the voltage drop at start-up and harmonic interference, based on the effective, project specific grid topology. The following evaluation process allows to identify, within those suitable combinations, the technically and economically most interesting solution. Within this evaluation, technical aspects (aerodynamics and system-integration) as well as life-cycle cost for fans, drives and wiring are considered. These costs include initial investment, maintenance as well as intermediate replacements when components do not fulfil the needed lifetime.

The developed best practises are transparent and easy to use and therefore a useful tool when designing a road tunnel ventilation system.

Keywords: Best Practice, Fan- / Drive Technology, Selection Process, VFD, DOL, Life-Cycle Cost

1. INTRODUCTION

When designing the ventilation systems of road tunnels and safety tunnels, the question of possible combinations of fan and drive technologies and their evaluation regarding technical realisation and economic efficiency arises on a regular basis. Hence, a well-founded and concise knowledge base for the selection of suitable combinations is only partially available. Therefore, the selection is often based on personal preferences and the experiences of the persons involved.

The research project summarizes the relevant basics (aerodynamics and fan technologies, tunnel ventilation specific system requirements, drive technologies and grid compatibility) and confirms / extends these findings by on-site measurements. Based on these findings, a four-step selection and evaluation process is developed allowing confirming the technical compatibility of a fan / drive combination and to evaluate the most suitable solution for a specific project / application. This so-called most suitable solution is determined using technical criteria such as the capability to precisely control the longitudinal airflow (in case of longitudinal ventilation) or the energy consumption and using life-cycle cost (25 years) including initial investment (fan, drive, cable system), annual maintenance as well intermediate refurbishment for components having a life expectancy less than the considered period.

2. BASICS

2.1. Fan-Technology

Fans are subdivided according to the curvature of the flow in axial, semi-axial and radial. In tunnel ventilation applications, mostly axial fans are used – other fan types (e.g. radial fans) are rather exotic and are therefore not covered by the present research.

Besides the basic fan type, a distinction can be made based on how the duty point is varied. Common techniques are throttling, variation of rotational speed, variation of pitch angle and variable inlet guide vanes. However, in tunnel ventilation applications, most often variation of pitch angle and variation of rotational speed are used. Hence, only those two techniques are considered in the research project. Figure 1 shows the fan characteristics of a fixed pitch fan with variation of rotational speed as well as the characteristics of a variable pitch, fixed rotational speed fan. The main differences are the size / position of the stall region and the characteristics of the aerodynamic efficiency.

When having to deal with initial counter-pressure (either caused by shaft pressures or by other fans), the extended operational region of a variable pitch fan is clearly advantageous and can determine the technical solution. Speed variation does not affect the stall limit and, depending on the effective fan curve, throttling of the other fans may be required to allow for a sequential start-up. According to [3], fans with variable pitch angle are also slightly advantageous regarding start-up time. No significant difference exists whether the pitch angle is controlled by hydraulics or by electric drives.

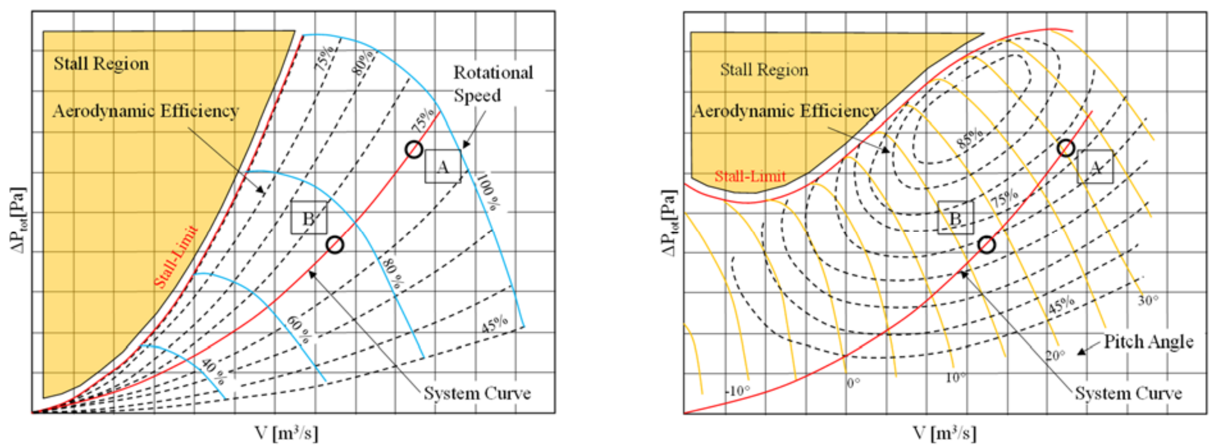

Figure 1: Comparison of fan characteristics affected by variation of rotational speed (left) and by variation of pitch angle (right). For a variable pitch fan, the stall region has much smaller extents and a stall-free zone is present at very low flow rates. For a fixed pitch angle fan, the aerodynamic efficiency remains constant along a specific system curve whereas in case of a variable pitch fan, the aerodynamic efficiency varies [2].

Regarding longitudinal ventilation for smoke management, the effect of a single jet fan on the airflow is an important characteristic. [4] presents a method to evaluate the airflow modulation by jet fans as well as considerations regarding proper acceptance criteria. This criterion will be used during the latter selection process.

2.2. Drive-Technology

Nowadays, most of the fans in tunnel ventilation applications are driven by three-phase squirrel-cage induction motors (asynchronous motors). Recent motor technologies such as synchronous reluctance motors appear to be very interesting regarding efficiency but, as up to now, no temperature rated motors are commonly available, asynchronous motors remain by far the most common technology. Significant electrical current peaks and corresponding grid perturbations occur when connecting the motor directly to the grid (direct online, DOL). Different drive systems allow limiting these current peaks at start-up: star-delta connection, pole-changing method (Dahlander Motor), soft starter, and variable frequency drive (VFD). Most often, the ratio of start-up current I_S to nominal current I_N is used to characterize these peaks.

In order to confirm literature as well as manufacturer data, on site measurements of the current and the voltage per phase are performed as well as measurements of the harmonics. When assessing grid compatibility, measurements must be performed using sufficient temporal resolution. According to [6], 10 ms RMS values have to be considered in order to sufficiently resolve the current / voltage evolution.

Table 1 summarizes the measured ratio I_S/I_N as function of the start-up method as well as the recommended value. One can see, that especially when using the pole-changing method, no significant reduction of start-up current peaks can be achieved. When using star-delta connection, the peak currents are reduced by a factor of two compared to DOL start-up. Even though soft starters theoretically allow for very low current peaks, in ventilation applications, the ratio of I_S/I_N cannot be reduced below 4 to 5 as otherwise, the available torque is not sufficient for driving the impeller. When using variable frequency drives, the current peaks can be ignored.

Table 1: Start-up currents for different drive technologies (measurement / recommendation)

Drive Technology	Tunnel	Measured I_S/I_N	Recommendation I_S/I_N
Direct online (DOL)	Tunnel Fluelen, exhaust fan	7,5	8 – 10
	Tunnel Fluelen, jet fan	7,9	
	Tunnel Islisberg, jet fan	11,3	
Star-delta connection (Y/D)	Tunnel Sachseln, exhaust fan	4,1	4 – 6
	Tunnel Islisberg, exhaust fan	4,6	
	Tunnel Gubrist, exhaust fan	4,1	
	Tunnel Uetliberg, exhaust fan	4,0	
Pole-changing method (Dahlander: 50% / 100%)	Tunnel Sachseln, safety gallery fan	5,7 (0% → 50%) 9,5 (50% → 100%)	8 – 10
Soft starter	Tunnel Kirchenwald, exhaust fan	4,0	3 – 5
	Tunnel Lopper, exhaust fan	4,3	
Variable frequency drive (VFD)	Tunnel Fluelen, exhaust fan	1,04	1,0 – 1,5
	Tunnel Saas, exhaust fan	1,27	
	Tunnel Crap Teig, exhaust fan	1,03	

Besides limitation of current peaks at start-up, pole-changing connection and variable frequency drives also allow for different rotational speeds and therefore for different duty points. Whereas pole changing motors only allow for a fixed, predetermined ratio of rotational speeds, VFDs allow to specifically adjust the rotational speed in order to match, as close as possible, the requirements. This allows for adequate controls (e.g. longitudinal smoke management) and important savings in energy consumption. However, for VFDs with rated power less than about 100 kW, the VFDs efficiency is strongly affected by the effective load (rotational speed /

torque). Figure 2 shows the VFDs efficiency as function of rated power and as function of the load (100% / 50% rotational speed) of a fan application. One can see that for mid-size VFDs, efficiency is reduced by 5% to 10% when operated at 50% nominal speed. Especially for very small VFDs, the efficiency drops by nearly a factor of two, strongly affecting overall efficiency. This is mainly governed by the power needed to drive the electronics of the VFD becoming important compared to the power of the driven machine.

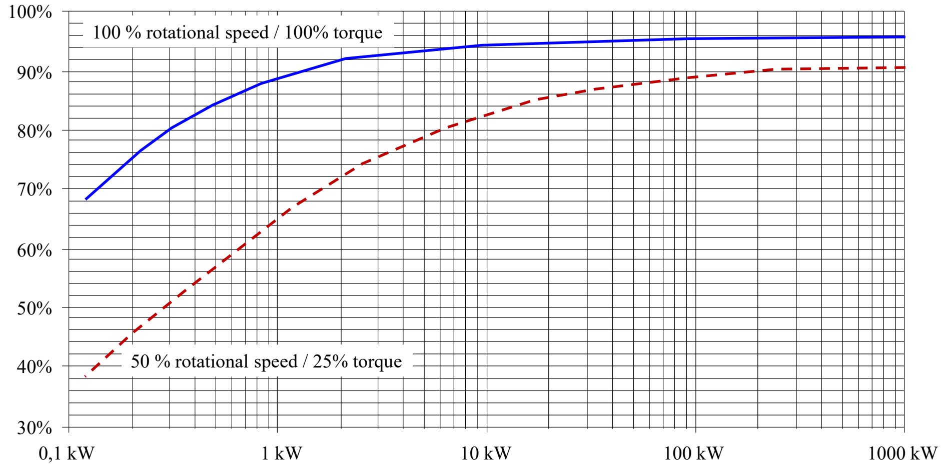

Figure 2: VFD efficiency as function of VFD rated power and rotational speed for applications with quadratic speed / torque relation [5]. For a 500kW VFD (typical exhaust fan), efficiency drops by about 6% when the rotational speed is reduced to 50%. In case of a 15 kW VFD (typical safety gallery / escape route fan), the reduction is roughly 10%.

2.3. Grid Perturbations

Grid perturbations can impact the selection of drive technology as well as its technical details. Hence, it's recommended to do first evaluations regarding grid compatibility already in the early design phase. Otherwise, cost relevant measures are required in case grid compatibility is not fulfilled during commissioning.

According to [6], grid perturbations are evaluated using the two following criteria: voltage drop (switching related voltage changes) as well as harmonic interference.

Voltage drops may cause sudden shutdown of equipment, loss of data in control systems as well as sudden relay-switching operations. Therefore, voltage drops need to be limited to tolerable values. Such values are given by technical rules [6] applicable in Germany, Austria, Switzerland, and Czech Republic. Hence, the voltage drop shall be limited to 3% at mid-voltage level (1 kV to 36 kV) and to 6% at low-voltage level (< 1 kV) being usually the secondary side of the transformers. The voltage drop is estimated, during the design phase, by the ratio of switched power and the short-circuit power at the corresponding voltage level. The data from Table 1 can be used to determine the switched power. The short-circuit power is either the power of the transformer divided by the short-circuit voltage (at mid-voltage level) or the grid specific short-circuit power.

Harmonics have a negative impact on the power quality and should therefore be avoided. Depending on their type[1], frequency converters and soft starters generate harmonics with different harmonic currents. An assessment of the harmonics according to [6] should only be performed if loads causing harmonic interferences are operated within the considered grid. The harmonic spectra of individual installations were measured and compared during the field tests. Harmonics can be reduced either by adding line chokes / filters or by more advanced VFD-

[1] E.g. 6-pole drives, 12-pole drives, active front end drives

types. According to the on-site tests, line chokes are appropriate to reduce harmonic currents for 6-pulse VFDs. In case of AFE VFDs, harmonics are normally not critical. During the design phase, harmonics can be assessed by evaluating the ratios of short-circuit power S_{kV} to installed power S_A and harmonics relevant power S_{OS} to installed power S_A. Depending on the voltage level, measures may be required or not as shown in Figure 3.

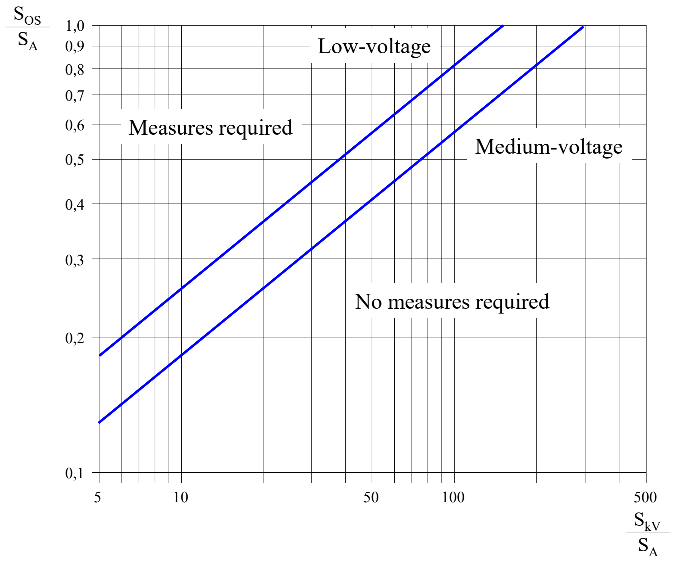

Figure 3: Evaluation of the need for measures to reduce harmonics for low- and medium-voltage installations, [6]

3. SELECTION AND ASSESSMENT PROCESSES

The research project [1] presents for each basic type of ventilation application (smoke extraction, longitudinal ventilation, and escape route ventilation) a four-step process to determine the project specific compatible solutions and, considering an estimation of life-cycle cost, the best option within those compatible solutions (see Figure 4).

In the following, this process is presented in more detail using the generic example "Tunnel Musterloch", being a bidirectional road tunnel of 1'300 m length. According to the system design, on overall thrust of 3'700 N is required for longitudinal ventilation. This thrust can be obtained by either 12 22 kW jet fans with nominal diameter of 630 mm, 8 30 kW jet fans with nominal diameter of 800 mm or 5 37 kW jet fans with nominal diameter of 1120 mm. According to the system type, the ventilation system must allow for proper airflow control. Hence, the effect of a single jet fan on longitudinal airflow shall not be bigger than the defined threshold (e.g. less than 0.4 m/s). If this is not the case, either the drive technology must be adapted or a jet fan with less standstill thrust has to be selected. Using the findings presented in [4] or any other calculation method for the impact on longitudinal ventilation, one can determine that, from a pure aerodynamic point of view, the 22 kW jet fan as well as the 30 kW allow for suitable airspeed control independent of the associated drive whereas the 37 kW jet fan needs to be equipped with VFD. Details of this evaluation process can be found in [1].

When assessing grid compatibility, the voltage drop as well as the harmonics need to be evaluated. The full report, [1] presents in detail the different steps to perform. However, it must be noted that no general rule exists as the grid compatibility depends on the effective topology of the installation (e.g. the installed power and the ventilation-related power per transformer). Depending on the overall power and depending on the chosen connection point, it may result that based on voltage drop, any drive technology and especially DOL is admissible for the 22 kW as well as for the 30 kW jet fan. As for the 37 kW jet fan, VFD is needed due to aerodynamics, voltage drop is not an issue. However, in order to limit harmonics, rather low-tech VFDs (6-pulse) may only be allowed when using line chokes / complex filters. Technically more advanced VFDs (e.g. AFE drives) are less problematic regarding harmonic perturbations.

Having defined the admissible solutions, these can be assessed regarding their technical quality. In case of longitudinal ventilation, the corresponding criteria are: the required space (within the technical rooms), the degree of grid perturbations (voltage drop, harmonics), the energy efficiency, the performance to control the airspeed in case of an emergency (accuracy, time needed to obtain the required airspeed), the complexity of the integration (e.g. relays vs. a complex, specific communication protocol), the cabling system (e.g. number / diameter of the power cables), the eventual impact on HVAC systems in the technical rooms (e.g. in case of VFD). Each of these criteria has its own weighting factor which can be individually adjusted. This allows to consider, at best, the project specific boundary conditions. The grading of each individual solution is given by this weighting factor and a predetermined baseline evaluation. More details regarding the technical evaluation can be found in [1]. For the "Tunnel Musterloch", due to the more precise control of the longitudinal airspeed, the solution using VFD is technically advantageous compared to the others. Nevertheless, the 22 kW / 30 kW jet fans with DOL drive are valid options basically due to their technical simplicity. However, it must be noted that the use of the evaluation mechanism needs an appropriate expertise and awareness of the underlying mechanisms. Otherwise, by imprudently adjusting the weighting factors, any solution can be brought forward.

The financial assessment, the life-cycle cost evaluation, considers the initial investment for the fans including drive and wiring as well as the maintenance costs. The estimate is based on the project specific solution as costs are determined among other things by the effective number of jet fans, by their specific drive, their nominal power, and cable length. The maintenance costs integrate annual maintenance as well as eventual component replacement e.g. for soft starter / VFD as their typical life expectancy is less than the considered life-cycle of 20 years (in case of longitudinal ventilation). Regarding the life-cycle cost within the example case "Musterloch", the most economical solution is the 30 kW jet fan with DOL drive. However, the difference to the 37 kW jet fan equipped with AFE VFD is only about 10%. It has to be noted that the cost evaluation is relative and does not allow for any estimate of absolute investment / maintenance cost as underlying prices (e.g. the price for metals) may have changed in the meantime.

When combining the technical and the economical evaluation for the "Tunnel Musterloch", the technical advantages of the 37 kW solution with VFD do compensate the higher life-cycle cost and so the recommended solution is to equip the tunnel with 5 37 kW jet fans, driven by active front end VFDs. Also, this overall result must be checked appropriately as even small differences may bring forward either of the solutions. Nevertheless, the results allow to distinguish in a quantitative, comprehensive manner the advantages / disadvantages of the individual combinations of fan technology / fan type and the corresponding drive.

Besides the detailed process for longitudinal ventilation, the research report also presents the corresponding processes for exhaust systems as well as for ventilation systems for escape routes / safety galleries

Figure 4: Overview of the selection and assessment process for the basic ventilation system types

4. SUMMARY AND CONCLUSION

To overcome repeated discussions regarding the most suitable combination of fan and drive for a specific project, the ASTRA research project AGT 2015-005: Analysis of systems formed by fan- and drive technology used for tunnel and safety tunnel ventilation presents a best practice process to determine on one hand the technically suitable solutions (from an aerodynamics and grid compatibility point of view) and, on the other hand, to compare the technical benefits and the life-cycle cost of those solutions. As the method is available for smoke extraction fans, for longitudinal ventilation systems as well as for the ventilation systems of safety tunnels, most of the applications are covered. Hence, a transparent and profound tool is created and can readily be applied during the design phase to compare different technical solutions as well as to determine the most suitable one.

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