

Automatic HVAC Air Recirculation Made Easy with Stepper Motors

Abstract

This technical note highlights the system requirements and operating conditions of automatic air recirculation valves and reviews compatibility of existing actuator types with these requirements. When comparing the available technologies, it becomes clear that air recirculation flap actuators containing a bipolar stepper motor offer key advantages over actuators with other motor types. It is shown how specific bipolar stepper motor drive techniques

The automotive HVAC market is mature, yet still subject to high-end innovation. Fuel economy, comfort and safety are the major drivers for change. In simple HVAC systems, a continuous inflow of fresh air is conditioned and brought into the cabin. This air leaves the car through some ventilation openings. Typically the driver can select, by means of a manual control function, whether the fresh air supply needs to be interrupted (recirculation) or not (fresh air open).

In recirculation mode, high-end HVAC systems monitor several cabin air parameters, recirculate the air through the air conditioning unit back into the cabin and limit the fresh air inlet to the minimum, while fulfilling the air parameters set by the driver and/or the system's specifications.

In theory [1], such automatic recirculation can reduce the fuel consumption of an HVAC system by 35%. Depending on the climatic conditions and driving cycles, an HVAC system can consume up to three litres of fuel per 100 km [1]. This indicates that large cars that are equipped with a low-end HVAC system will benefit the most from the

Climate control systems are one of the larger consumers of power in modern cars. In particular, the compressor consumes thousands of Watts when operational.

One of the ways to reduce the energy consumption of climate control systems is to improve compressor efficiency. However, a more important method for saving energy is to reduce the "active time" of the compressor. In order to do this, we need to look downstream at the compressed refrigerant flow and verify what really happens during compressor operation.



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can contribute to the overall system performance while the total system cost is minimized. The technical note elaborates on availability and key features of motor driver integrated circuits that allow advanced control of these novel actuators.

INTRODUCTION

addition of an automatic recirculation function. However, small-and medium-sized cars that have advanced engines with low CO₂ emissions will also benefit from a smart air-recirculation flap because the contribution of the HVAC fuel consumption is relatively high.

Forecasts indicate that the percentage of cars equipped with a semi-or fully-automatic HVAC system will increase year-on-year. At the same time, the introduction of CO₂ refrigerants leads to the potential requirement for additional sensors to be mounted in the cabin. These trends mean that the CO₂ and IAQ (Interior Air Quality) sensor technologies already available will increasingly be reused in small cars and/or in cars with low-specification HVAC systems.

While the sensor aspect of the automatic recirculation function may have been solved, there is still some work needed to tackle the issues around flap motorization. This paper will focus on the recirculation function, system requirements, the air flap actuator and the driving of that actuator.

AIR RECIRCULATION SYSTEM

The efficiency of an HVAC system largely depends on the amount of refrigerant supplied to the evaporator. Replacing the mechanical expansion valve with an electromechanical valve controlled by a linear stepper-motor has previously been proposed [2] to gain better control over the flow of the refrigerant. Alternatively, the average temperature of the airflow that runs over the evaporator could be decreased (if the evaporator is exposed to cooler airflow, then a smaller refrigerant flow is required, meaning reduced compressor activity). The lower temperature of air flowing over the

evaporator can be accomplished by re-using, to a large extent, the cabin air that has already been cooled rather than the relatively warmer air from outside of the vehicle. This mixing of the correct amount of fresh air and cabin air can be performed by an automatic recirculation valve. This recirculation function is a key element in the overall energy efficiency of the HVAC system and special care has to be taken to assure correct and optimized operation over the lifetime of the car. Let us now look at the different system elements and important parameters and requirements for the recirculation function.

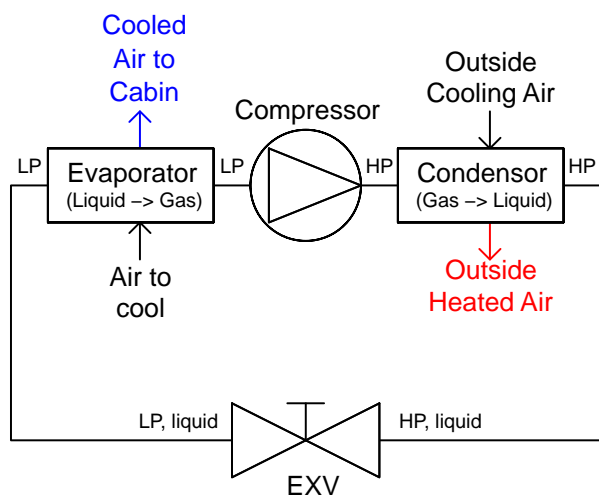


Figure 1. HVAC System

Sensors

The adaptive air recirculation system will need to continuously monitor the quality of the cabin air. A lack of sufficient fresh air can lead to discomfort, headache and drowsiness and, because this is not immediately noticed by the driver, can result in potentially dangerous situations. One of the dominant indicators of fresh air consumption by humans is the decrease of O_2 and the increase of CO_2 and H_2O . Nowadays, CO_2 sensor technology is available from several Tier-1 and Tier-2 manufacturers, while O_2 or H_2O sensors could also be used for sensing changes in the cabin air composition. These interior air quality sensors differ from the exterior air quality sensors, which focus on detecting polluted air and preventing it from entering the cabin. The minimum requirement for a good adaptive air recirculation system is a closed loop control based on interior air quality. As well as the controlled – yet still acceptable – decrease of fresh air, a slight increase of humidity might be observed. This, however, depends largely on interior and exterior conditions, HVAC system parameters, cabin volume and the number of passengers. In any case, because the interior air will be recirculated over the evaporator, it will be continuously dried. From this observation, it is not expected that the windscreen will show increased fogging (hence the installation of an additional fogging sensor might not be required).

Evaporator

The condensed water from the evaporator will need a high-quality drain and good separation from the heater-core. This is to prevent the water from re-evaporating (which would increase humidity in the cabin). Furthermore, to avoid recirculation of germs and bad odours from the evaporator, an active sterilization system (e.g. UV-light) at the evaporator should be considered. Note that this also applies to HVAC systems that have no automatic recirculation.

User Interface

The user interface to the ON/OFF recirculation flap today is typically a push-button. Pushing the same button several times, the recirculation flap is opened or closed, while an LED indicates the state of the flap. With the addition of a second LED, one could enter and indicate a third state called “automatic recirculation”. This second LED will require only minimal dashboard space and no other hardware changes.

Electronic Control Unit

The Electronic Control Unit (ECU) operates the recirculation function based on the readings from the sensor and a pre-set value. The ECU closes the control loop of the fresh air regulation and operates the recirculation flap actuator (Figure 2) in order to maintain the required CO_2 levels. The frequency of operation of the circulation flap is a function of the maximum allowed number of occupants, the minimum volume of air in the car interior and the maximum allowed deviation from the desired CO_2 level. It is easily calculated that five people in a 3 m^3 interior will increase the CO_2 concentration by 100 ppm within 30 s.

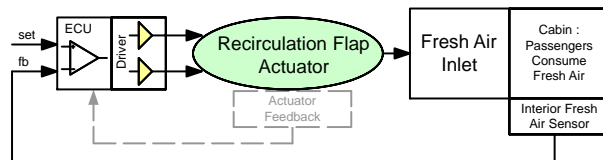


Figure 2. Automatic Recirculation System

The air recirculation control loop requires mainly low-speed interventions to compensate for pressure and airspeed changes in the “Fresh Air Inlet” (Figure 2). This happens frequently when the driving speed varies, for example in – or in the vicinity of – cities. The airflow through the fresh air inlet also changes when the pressure at the suction side of the blower changes with blower speed. For optimal control, a (low-noise) blower induces a variable airstream across the evaporator to compensate for fluctuations in sunlight (e.g. due to a winding road or intermittent shade caused by buildings, trees or clouds). As a result, the variable amount of fresh air through the air inlet needs to be matched with the constant production of CO_2 by the occupants. The continuous but slow adjustment of the recirculation flap setting can easily be accommodated within the execution time of existing software cycles.

However, the software algorithm itself will require special attention because it is a matter of safety to ensure that the driver is supplied with the correct amount of fresh air under all circumstances.

Flap Actuator

The air recirculation flap actuator is a small motorized valve that is operated by means of a driver inside the ECU. The function of the flap is to control the amount of outside

air that will flow into the cabin. The metering of this amount is relatively simple and is handled by means of a damper or a butterfly valve. For stable control algorithms, the flap position should be known at all times, so some sort of position feedback is a must. Because the control system is frequently re-adjusting the actuator position, contactless operation of the motor and sensorless position feedback is desired. The following discusses in more detail the requirements of the flap actuator.

RECIRCULATION FLAP ACTUATOR MAIN OPERATING CONDITIONS AND REQUIREMENTS

The flap actuator is positioned in the HVAC system, which is already relatively bulky due to the air-ducts. As in most automotive systems, the weight and size of the actuator are important parameters. Typically, the actuator consists of a plastic housing, an electric motor with connector and a gear-reduction system and, sometimes, a position sensor. Because of the different materials involved, there are many factors influencing weight and size of actuators. Over the years, companies have found ways to balance required motor torques against gear-ratios and to optimize actuator weight and size for a given functionality. Despite this there is still some room for improvement, not least in the removal of position sensors and the introduction of new motor technologies.

Low acoustic noise is another important consideration as the actuator is operating in an airstream that flows directly into the passenger compartment. Furthermore, the flap is continuously operated (new target positions are frequently given) and acoustic noise should not increase significantly over life.

The position update rate depends on the application software loop-time and is, for example, every few seconds. Between these position updates, the actuator is required to hold its last position despite the application of any external torque to the flap (e.g. from a bump in the road or increased wind speed air pressure). This means that the actuator should

be able to maintain position (holding torque) under the influence of external forces – ideally with minimum current consumption. The actuator also needs to be robust enough to run once in a while against an obstruction such as an end-stop. The recirculation flap is operated typically at or near its “closed” position. Suppose that an HVAC system is designed for a car that is able to carry five persons. The air inlet is then designed to supply enough fresh air for comfortable driving of all people at average speeds. However, average car-occupancy is only slightly greater than one. Taking into account increased air pressure at elevated speeds, it becomes clear that, for most of the time, the range of flap operation will be within the first 20% of its full range.

This puts a quality requirement on the mechanical and electrical stability of the actuator: it needs to be stable enough to move continuously during its life in a relatively limited position range with no degradation on motor, sensor or gears. Other factors that need to be considered are that the operation of the actuator should have low EMC emissions and the cost of the actuator, the cost of the required driver in the ECU and the cost of the wiring between ECU and actuator should be as low as possible.

Let us now have a look at some available HVAC flap actuator technologies and discuss their fitness for use in an automated recirculation flap.

AVAILABLE RECIRCULATION FLAP TECHNOLOGIES

Several solutions exist to move HVAC air flaps, including the recirculation air flap. They differ in type of motor used in the flap actuator and the specifics and features of the motor control.

Brushed DC Motors

A brushed DC (BDC) motor is an internally commutated electric motor, which rotates when voltage is applied to its two terminals. It does not require a controller to switch current in the motor windings; the commutation of the windings of a BDC motor is done mechanically. A segmented copper sleeve, called a commutator, resides on the axle of a BDC motor. As the motor turns, carbon brushes slide over the commutator, coming in contact with the different segments. The segments are attached to different

rotor windings; therefore, a dynamic magnetic field is generated inside the motor when a voltage is applied across the brushes. BDC motors are made in a mature and relatively inexpensive technology. Only two wires lead from the driver to the motor terminals. It is simple to control a BDC motor; e.g. bidirectional drive can be achieved by means of two transistor half-bridges. In case position feedback is required – as with the air recirculation flap – a position sensor needs to be added. A variety of sensors exist, the most common being Hall Effect sensors and potentiometers. This sensor (e.g. a potentiometer as depicted in Figure 3) together with the associated ECU wiring and the impact of the size of the electrical connector makes up a significant part of the system cost.

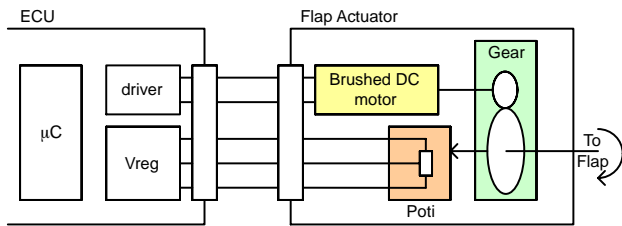


Figure 3. Brushed DC Flap Actuator with Sensor

Other – often patent-protected – techniques exist (e.g. pulse-count), which operate without sensors but with additional complexity to the motor driver and control algorithm. It is also important to note that the brushes and commutator are the parts of a BDC motor that are most prone to wear. Because of the need for frequent operation of the air recirculation flap, brush degradation puts a stress condition on the long-term mechanical reliability of a recirculation flap equipped with a BDC motor. The brushed commutation principle in BDC motors also means continuous and quick switching of high currents into a highly inductive load, which can cause sparking at the commutator. Electrical arcs such as these emit electromagnetic radiation in the form of an electric field across a wide band of the spectrum; hence special care needs to be taken to meet the state-of-the-art Electro-Magnetic Compatibility (EMC) requirements.

Stepper Motors

A stepper motor is a synchronous electric motor that divides a full rotation into an integer number of steps. It is brushless and hence not prone to mechanical wear-out linked to brush commutations. A stepper motor has a fixed amount of “phases” equal to the amount of “toothed” electromagnets arranged around a central gear-shaped piece of iron. The electromagnet is energized by an external circuit controlling the voltage or current in the electrical winding around the electromagnet. Using a proper electromagnet energizing scheme, the motor can be turned by a precise angle.

Unipolar Stepper Motor

A unipolar stepper motor has two windings per phase. These windings are electrically connected with the ECU as depicted in Figure 4 and, as with the BDC motor solution (with sensor position feedback), typically requires five wires. The choice of using unipolar stepper motors in motorized valves has mainly been dictated by the availability of low-cost driver ICs or driver circuits; e.g. a 4 low-side driver circuit. Like BDC motors, they are often present in the (semi-)automatic HVAC systems found in low- to medium-end cars. One drawback of the unipolar

approach is that only half the number of windings are energized at any time (basically the unipolar stepper motor carries double the amount of copper than that required to move the motor).

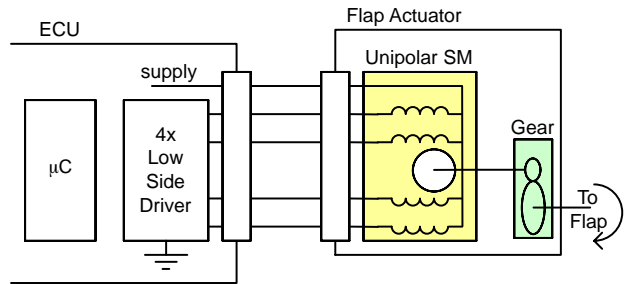


Figure 4. Unipolar Stepper Flap Actuator

Bipolar Stepper Motor

A bipolar stepper motor has one winding per phase. Compared to a unipolar motor, this gives a size and weight advantage because the amount of copper in the winding is roughly half of that for a bipolar motor with similar motor characteristics. This is an important benefit of the bipolar stepper motor architecture, as it allows engineers to achieve optimal energy economics with minimum volume and weight. The two windings are electrically connected with the ECU as depicted in Figure 5, so typically only four wires are needed for motor operation (compared to five for a unipolar stepper motor or a BDC motor with sensor). A bipolar stepper motor is typically driven by a dual full-bridge transistor combination, one for each winding. Automotive-qualified bipolar stepper motors for mechatronics flap actuators have existed for many years and are found in high-end HVAC systems. These motors can now be re-used for a dedicated low-cost air-recirculation valve with a drive configuration as depicted in Figure 5. Here the stepper motor driver is located inside the ECU and is connected by means of only four wires to the sensorless actuator.

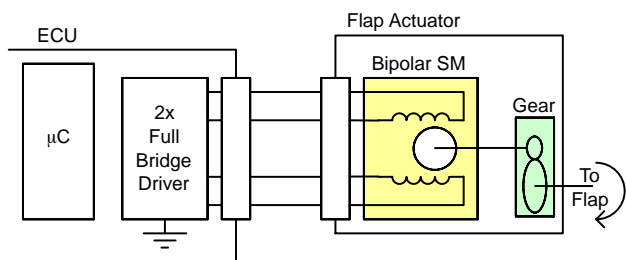


Figure 5. Bipolar Stepper Flap Actuator

STEPPER MOTOR DRIVER TECHNOLOGY

Advanced stepper motor drive technologies have been developed to optimize actuator operation in terms of factors such as acoustical and electrical noise production and long-term reliability. Compared to traditional architectures, new bipolar stepper motor actuator technologies offer a balanced solution: more system benefits (i.e. an optimized mix of features and quality) without overall system cost penalties.

Micro-Stepping

Basic movement of a stepper motor is accomplished by switching the windings, which energize the electromagnets, in an alternating on/off fashion. This is called a “full-step” movement because it aligns the rotor to the stator tooth-by-tooth or step-by step. This is a rough mode of operation and can cause the system to vibrate, contributing to increased acoustic noise during operation. Another possible effect is loss of steps, (i.e. steps are skipped). Without proper design this means that the system is no longer aware of the exact actuator position. These effects can be avoided or at least alleviated by operating the stepper motor in micro-stepping mode, meaning that the windings are energized together in such a way that the motor moves from step to step position via several sub-positions or micro-steps. Moving the motor in this more continuous way has a positive impact on the stability of the motor system and results in better performance in terms of acoustic noise and step-loss avoidance.

Sensorless, Closed-Loop Operation

Most stepper motor driver operating schemes use an open-loop principle and, due to the lack of feedback in the system, the stepper motor has to be over-dimensioned to avoid unnoticed step-losses in all system-relevant cases (which are a function of, for example, motor load). Over-dimensioning can be reduced by means of a closed-loop approach using sensorless step-loss detection. Stepper motors inherently contain a “virtual” sensor; the motor’s operation modes (running at speed, stall condition, etc) can be deduced from monitoring the backelectromechanical force or the bembf signal.

Reliable End-Stop Detection and Accurate Proportional Control

Air-conditioning flap control actuators can also benefit from this bembf sensor capability. A stepper motor driver, with an embedded stall detection algorithm based on the bembf signal, allows the system to detect very accurately the end-stop of a flap in an HVAC air distribution channel. Typically this end-stop is reached on purpose during a movement – for example when the flap is operated in a near-closed position. Hitting the end-stop can also happen due to erroneous operation or because of small mechanical tolerances. Typically more than a thousand full steps are required to bring a flap from a fully opened to fully closed position. Because of the gear construction inside the actuator

and the thermal expansion of the air-ducts and mechanical tolerances around the flap, the full stroke of an actuator can change over tens of full steps. Now it is important to realize that the amount of air that flows through a nearly closed flap is a non-linear function of the flap position. As a result, for a flap that controls small amounts of airflow, a relatively large error on the airflow is seen. So to control accurately and fully proportionally the amount of air flowing through an HVAC duct, an adaptive and closed loop algorithm must be employed. The closed-loop aspect (or merely pseudo closed-loop) consists of running deliberately into stalled condition once in a while. The stall detection then allows accurate marking of the new positions starting from the fully closed flap position. By doing this, even the smallest flap-openings can be maintained accurately and reached repeatedly, yielding true proportional control. It is clear that this mode of working offers advantages over traditional methods that utilize open-loop absolute positioning based on counting steps. Because these methods cannot regenerate a reference position, any permanent root cause for position offset (like step-loss from an overload condition) needs to be avoided, resulting in an over-dimensioned, hence sub-optimal system. Other methods (without stall detection) are relatively blind to where the exact end-stop position is. Hence to be sure that the end-stop is reached in a referencing run, these methods require driving the stepper motor multiple steps beyond the estimated end-stop position. This results in a blocked motor with associated acoustic noise and mechanical as well as magnetic wear-out. To guarantee the long-term reliability, a special type of actuator is required, which survives the mechanical vibrations present in this mode of operation. Now a device that detects the end-stop within one full-step will avoid the noise and vibration during the stall condition. Stall detection within a single full-step also allows the rotor and stator-magnetic fields to remain synchronized. This avoids any risk of magnetic wear-out caused by demagnetization of the rotor due to AC magnetic fields from the stator, and will help to maintain a stable actuator torque over life-time.

Adaptive Speed Control

Speed-critical positioning is important in situations in which a flap needs to be closed as fast as possible: e.g. closing of the recirculation flap when an exterior sensor detects the presence of polluted outside air. The back-emf signal makes speed critical operation possible for stepper motors by means of dedicated adaptive-speed motor drive algorithms. This allows stepper motors to challenge one of the main advantages of brush DC motor actuators, notably the ability to rotate as quickly as the supply voltage and load allows. The stepper motor is operated at the fastest speed possible, adapting speed automatically to the actuator and flap characteristics (e.g. load). During this adaptive-speed operation, sensor-less stall detection is operational,

guaranteeing error-free positioning. These algorithms allow speeds up to 1000 full steps per second.

Resonance Avoidance

The bemf signal proves to be very useful, not only for stall detection and adaptive speed control, but also for trouble-shooting resonance issues. A first difficulty with solving resonance issues is that a suitable sensor cannot be

attached easily to the system. A second difficulty is that a mounted sensor should not change mass or friction of the motor-axis, as this alters the resonance behaviour being measured. Now this is solved easily if the resonance behaviour and related rotor-movement is observed through the “embedded virtual sensor”. Please refer to [3] for more information.

FLAP ACTUATOR TECHNOLOGIES SUMMARY

Table 1 summarizes the “fit for use” of the flap actuator technologies discussed. Both brush DC and unipolar stepper motors offer their advantages but also show weak points.

The bipolar stepper motor technology seems to offer the best of both worlds and is compatible with all reviewed requirements.

Table 1. SUMMARY OF ACTUATOR TECHNOLOGIES

Actuator Characteristic	Brush DC	Unipolar Stepper	Bipolar Stepper	Comment
Wear-Out & Durability	–	++	++	No Brushes in Stepper
Audible Noise	–	+	++	Microstepping in Bipolar Stepper
EMC	–	+	+	Commutation Sparks in Brushed Motor
Holding Torque	–	++	++	Hold-current in Stepper
Sensorless Operation	+	++	++	BDC Requires Pulse-count if Sensorless
Cost of Control Circuit	+	++	–	Unipolar Requires only 4 Low-side Switches
Cost of Motor	++	–	++	Unipolar Stepper has 2x Cu vs. Bipolar
Number of Wires	2 to 5	5	4	
Stall Detection	++	–	++	Recently Developed for Bipolar Stepper
High-speed Flap Closing	++	–	++	Recently Developed for Bipolar Stepper

It is up to the Tier-1 HVAC system manufacturers to assign the correct weighting to all these functions. Observation: the system level cost is comparable for the

three actuator types, however if only the purchasing cost of the motor driver itself is taken into account, then the car manufacturer might end-up with a sub-optimized solution.

DRIVER INTEGRATED CIRCUITS

Integrated circuits that drive bipolar stepper motors according to the technologies described in “Stepper Motor Driver Technology” section are now available. A typical block diagram of such an IC is shown in Figure 6. This IC is placed inside the ECU and two full H-bridges drive the two phases of the bipolar stepper motor. The ECU’s microcontroller communicates with the IC via an SPI interface and a set of dedicated signals. A current translator table, embedded in the driver applies the correct current to the windings. The microcontroller needs to set only once the SPI registers that define the winding current peak value, micro-step mode and default direction of movement. After this, the micro can step through the translator table by applying only “next” signals to the IC (see NXT pin in Figure 6). The motor driver then takes full responsibility and generates the requested current waveforms for full-step, half-step or sinusoidal micro-step motions. The speed of

applying the “next” pulses defines the speed of the motor movement while the state of the “direction” pin (see DIR pin in Figure 6) defines the direction in which the motor rotates.

A simple but highly effective stall detection algorithm is implemented and can be activated by means of the SPI bus. For more advanced control, the sensorless function provides motor bemf samples, which can be read out via SPI communication. The collected samples can then be used, for example, in an adaptive speed control algorithm for closing the recirculation flap at maximum speed.

The HVAC system’s electronics need to be protected against stress and error conditions, which are potentially present in automotive applications. Therefore, proper diagnostic functions are implemented to detect all relevant error conditions and to prevent system and IC damage. The IC has an interrupt output pin to warn the microcontroller when an error occurs (see ERRB in Figure 6).

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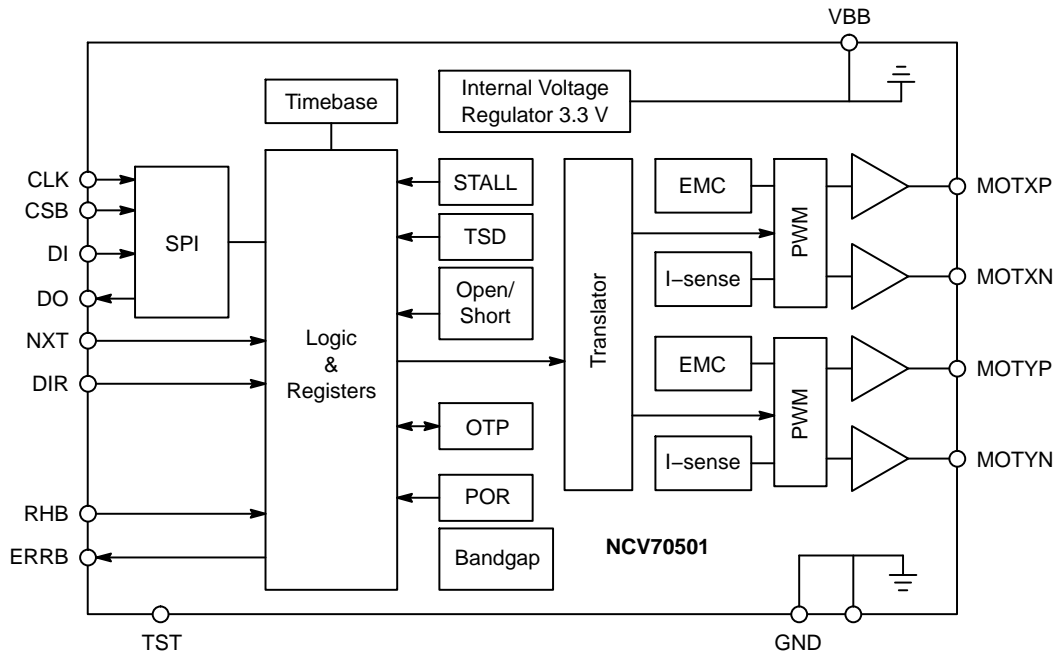


Figure 6. Bipolar Stepper Motor Driver IC (NCV70501) – Block Diagram

CONCLUSION

Automatic air recirculation valves can contribute to fuel economy of small-and medium-sized cars. Existing flap actuator technologies have been discussed in view of operating requirements of such a recirculation valve. Both brushed DC motor actuators and unipolar stepper motor

actuators show incompatibilities with some of the technical requirements. A bipolar stepper motor valve in combination with a novel driver offers the best possible technical solution to meet the high-quality operation requirements of the air recirculation valves of the future.

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GLOSSARY

HVAC:	Heating, Ventilation and Air-Conditioning	EMC:	Electro-Magnetic Compatibility
IAQ:	Interior Air Quality	AC:	Alternating Current
IC:	Integrated Circuit	Bemf:	Back-Electro-Mechanical Force
ECU:	Electronic Control Unit	SPI:	Serial Peripheral Interface
UV:	Ultraviolet (light)	EXV:	Expansion Valve
LED:	Light Emitting Diode	LP:	Low Pressure
BDC:	Brush(ed) Direct Current (motor)	HP:	High Pressure

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