Efficient Motor-Driven Appliances Using Embedded Adjustable-Speed Drives

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ABSTRACT

Over the last four decades, power electronics technology has reduced variable frequency drive cost and size and improved performance through advances in semiconductor switching devices, drive topologies, simulation and control techniques, and control hardware and software. In this report, improvements in adjustable speed drive technology were applied to residential appliances that have not previously used adjustable speed drives (ASDs) to compare the energy used in non-ASD versus ASD appliances. These appliances included clothes dryers, refrigerators/freezers, and central and room air conditioning applications. Adjusting speed to meet the load provides smooth operation in addition to the elimination of start and stop transients under off-design, part load operation. With air conditioners, low speed compressor operation is equivalent to having a smaller compressor and correspondingly oversized heat exchangers, resulting in lower temperature differences and respectively higher equipment efficiencies. These benefits translate to lower energy bills, better controllability and overall smoother operation, greater equipment reliability, and appliances equipped with ASDs lend themselves to demand response (DR) programs. All these attributes align with desirable characteristics sought by residential consumers.

Introduction

The case study contained within this report was generated specifically for the state of California, but the energy savings benefits of adjustable speed drives (ASDs) in residential appliances are applicable anywhere. This work was performed by the Electric Power Research Institute (EPRI) for the California Energy Commission (CEC) with funding provided under its Public Interest Energy Research (PIER) program.

It has been known for decades that ASDs save energy. However, the energy savings benefit of using an ASD has only recently been appreciated within the residential market. The goal of the research in this paper was to demonstrate that the addition of ASDs to the design of widely used domestic appliances provides significant energy savings. When comparing standard, non-ASD versions to ASD versions of the same appliance type, this study found that just refrigerator/freezers could save as much as 1400 GWh/yr in California alone. Additionally, the research found that there are other, non-energy, benefits that should aid in fostering consumer acceptance. Proven published results will promote understanding and encourage the wider use of these energy saving techniques. The energy savings benefit will be further enhanced by improvements in demand response (DR) and power factor (PF).

Technical Overview

In order to understand how ASDs can be of a benefit to residential devices, it is important to form an understanding of how they operate.

Motor and ASD Technology

Electric motors are used to convert electrical energy into mechanical work. To increase energy efficiency this conversion requires a match of motor output power to the applied load power requirement. ASD technology provides a means of converting single phase power into an electrical format that provides energy efficient speed control for a three phase electric motor.

This technology allows a motor to closely match energy requirements to power delivery. Adjustable speed drive technology permits the use of a high efficiency three phase motor to convert electrical power to mechanical power and, in turn, displaces low efficiency single phase electric motors. This technology facilitates energy efficiency in domestic appliances and offers a variety of associated benefits that reduce material costs and avoid wear and tear.

The Fundamentals of an Adjustable Speed Drive

Adjustable speed drives are configured to manipulate the frequency provided by the utility and thus adjust the speed of the device. This is done by passing the AC input voltage from the utility through a full wave rectifier bridge (Figure 1). The output of the rectifier bridge is a relatively smooth DC supply. Additional "smoothing" is provided by a capacitor bank which serves as a source of reactive power for the motor. The smoothed DC voltage can be converted into the required output voltage and frequency by an inverter bridge circuit that uses pulse width modulated techniques.

Alternating polarity blocks of DC are sequenced such that the required voltage and frequency are produced. Change in voltage is achieved by increasing the width of the blocks. Change in frequency is achieved by the rate of change of polarity. Fundamental to the wave form generation is a base switching frequency which will be in the range of 2 to10 kHz. This Pulse Width Modulation (PWM) waveform is changed by the action of the motor into a sinusoidal current waveform providing efficient motor operation.

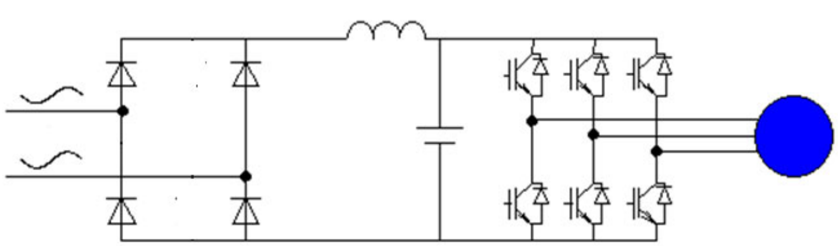

Figure 1. Voltage-Fed ASD System with Input Diode Rectifier, DC Link, Inverter and Motor.

The invention of the insulated gate bipolar transistor (IBGT) and the application of the digital signal processor (DSP) during the 1990s transformed the cost, size, and performance of adjustable speed drives. Performance increased whilst both cost and size decreased. These improvements are supported by the displacement of asynchronous induction motors by highly efficient, compact, synchronous induction motors. A tremendous change has occurred; there exists now a technologically superior drive, a motor with improved topology, and the availability of very efficient scroll or reciprocating compressors, a truly powerful combination. These motors are significantly smaller and more efficient than the single speed motors that are employed in nearly every household appliance today.

Electrically Commutated Motors (ECMs) are readily available. They are the most recent addition to the energy savings arsenal. Their major contribution to energy conservation is the displacement of low efficiency single phase machines with a high efficiency electric drive system. They can be used as fixed speed or adjustable speed delivery systems. They have high power factor input and very low losses. They can be used to replace evaporator and condenser fans in refrigerator/freezers and they are now commonly found in ceiling fans. (Figure 2)

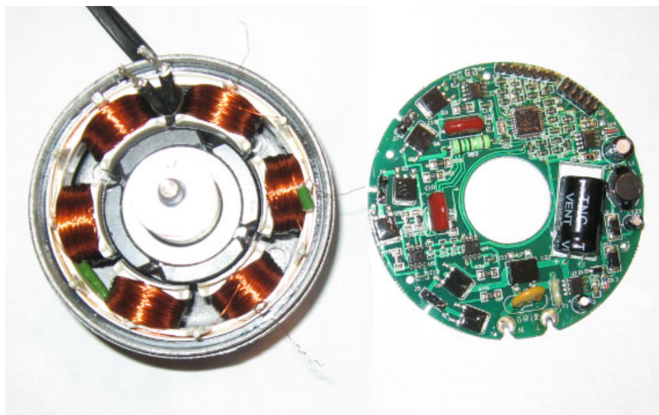

Figure 2. Electronically Commutated Motor (ECM).

The use of adjustable speed controlled motors captures a number of benefits. ECMs are effectively an ASD with a motor and they are used in place of conventional single phase motors. When adopted for use they can:

- Permit the use of smaller, lighter, and more efficient three phase electric motors. This reduces the cost of the equipment and the cost of manufacture as smaller quantities of raw materials are used. This is turn preserves raw materials and benefits the environment.
- Greatly reduce or eliminate start and stop noise events. Motor starting becomes gradual rather than abrupt and this avoids those noise transients that occur owing to the movement of compressor housings and refrigerant lines.
- Provide all the watt-less (kVar) power required by the electric motor. The capacitors connected to the DC link in the ASD provide all the reactive or watt-less requirements of the motor.
- Provide speed that is higher than the highest speed (3600rpm) available from single phase motors. The ASD can provide frequency higher than 60hz which enables motor speed to be limited only by the mechanical capability of the motor rotating parts.
- Provide external links for remote control that could be employed for programmed demand response. The ASD logic is readily adaptable for Wi-Fi control
- Operate at high power factor. The ECM/ASD power circuit contains modulation control that maximizes input power factor.
- Function efficiently using a three phase supply (20%-60% improvement over original single phase motor) and provide control over a wide speed range.

- Provide accurate speed control that avoids asynchronous induction motor “slip”. It eliminates losses associated with “slip”. This offers higher reliability as phase shifting items are eliminated.

ECMs/ASDs are currently used within a limited number of market available refrigerator/freezers, clothes dryers, ducted central HVAC systems, and ductless single room HVAC systems, those appliances types chosen for this study, and benefit in a variety of ways from the introduction of adjustable speed drive technology. Though available in the market please models have not been widely utilized. This lack of market penetration could potentially be from limited public exposure and education regarding the benefits of ASDs.

Opportunity

The use of ASD speed control in domestic appliances offers a number of advantages: energy savings, reduced noise, extended component life, lower environmental impact, and the availability of demand response. The greatest advantage remains yet to be harvested, namely a wider beneficial use of speed control in domestic applications. The results of comparative testing of familiar appliances, with and without speed control, as detailed in this report show that speed control offers very positive benefits to householders and utility providers. Industrial applications operating on three phase power have, for many years, been able to take advantage of the benefits offered by variable speed. The ECM effectively allows households that are provided single phase power to use appliances that operate on three phase. The challenge is to use the ECM and variable speed control to the fullest extent possible. The task is to identify where single phase motors are used, investigate the application, and consider the implication of switching motor type. Care should be taken to ensure the new application works seamlessly with the system, but essentially all heat pumps and air circulation fans would benefit from ASD control.

The inclusion of ASDs into residential devices such as refrigerators, HVAC systems, and dryers, lends itself to one additional energy savings benefit. Demand response up until recently has simply meant turning things on or off for a specified duration. The consumer is often very aware of the event because their central air conditioning is turned off in the heat of the day. However, ASDs provide a vast selection of new set points anywhere between 100% and 1% duty cycles that can reduce the energy demand on that grid, without negatively affecting homeowners. Not only will homeowners be less aware of DR events, but utilities can now call on devices that were previously impractical, such as refrigerators and freezers. These devices can now reduce their demand while maintaining performance. This leads to happier DR program participants that are more likely to remain in programs.

Test Results

Refrigerator/Freezer

Methodology. The testing procedure examined the operation of differently controlled compressors, one in each refrigerator. The results obtained from an ASD controlled compressor were compared with results from a standard single speed compressor. Separately, bench testing was performed on evaporator and condenser fans of the type typically found in refrigerator freezers. These components were tested with and without ASD control.

In testing the compressors, room temperature water was added to the refrigerator cabinet to simulate an average household usage pattern. Over a 24-hour period, water was replaced with room temperature water at regular intervals. All input power characteristics of each refrigerator/freezer were measured and recorded.

In testing the fans, the losses of conventional condenser fans were measured and compared with the losses of electronically commutated replacements. Similarly, losses in conventional evaporator fan systems were compared.

Results. During a 24 hour period the non ASD controlled refrigerator freezer unit consumed 4.6 kWh compared with the ASD controlled GE Profile that consumed 3.7 kWh. This is equivalent to savings of 19.6% or 0.9 kWh in a 24 hour period, which equates to 328 kWh/yr.

The improved energy performance demonstrated in this series of side by side tests was achieved by the use of an ASD controlled compressor. Additional energy savings may be obtained from the refrigerator by substituting energy efficient ECM fan motors for the standard low efficiency evaporator and condenser fan motors. The impact of the losses from the evaporator motor not only waste energy in the operation of the motor as it moves cooled air in the appliance but also the energy wasted heats the already cooled air thereby partially destroys the work carried out by the compressor.

Market research on California concluded that there are 18,000,000 refrigerator/freezers that consume a total of 15,787 GWh/yr. Extrapolating from tests results obtained, 19.6% savings could be expected from 100% market penetration of ASD controlled compressors in refrigerator/freezers. Therefore projected energy savings are calculated to be 3,094 GWh/yr, if 100% of California refrigerators were converted to units using ASD controlled compressors.

Predicted energy savings of 328kWh/yr (the values shown above from EPRI's laboratory testing) from each of 18,000,000 fridge/freezers in CA is equivalent to 5,904 GWh/year.

Clothes Dryers

Methodology and results. Table 1 summarizes the result of six total valid runs. Each test (slow or fast) was conducted three times in accordance with DOE test requirements. Run-to-run variation for per-cycle energy consumption was 13% for fast tests, and 8% for slow tests. In addition to describing energy consumed per cycle, we list the energy-weighted power factor, drying time, remaining moisture content (RMC) in the load at the end of the run, and the combined energy factor (CEF) for each run. RMC is calculated by taking the total weight of the test load after drying and subtracting the "bone dry" weight of test load before wetting. Then this difference is expressed as a percentage of the bone dry weight. Initial runs with the normal dryness setting did not dry the load enough, so the runs shown here were done on the highest dryness setting. Most of these were still not dry enough, but the runs are considered valid because there were no other options. CEF is the efficiency metric for clothes dryers as defined by the DOE 2013 test procedure. This efficiency metric is a ratio of the pounds of bone dry clothing dried and the total energy consumption of the clothes dryer (includes active mode energy consumption and standby mode energy consumption).

Table 1. Data summary for six valid runs

Speed	Energy Per cycle (kWh/cycle)	Energy Weighted Power Factor	Drying Time (min)	Remaining Moisture Content (RMC) of load	Combined Energy Factor (lbs/kWh)
Fast	1.14	0.82	88	2.3%	6.33
Fast	1.12	0.82	88	3.2%	6.46
Fast	1.27	0.83	99	1.8%	5.69
Average	1.18	0.82	92	2.4%	6.16
Slow	0.95	0.83	103	3.0%	7.55
Slow	1.02	0.83	109	3.0%	7.09
Slow	1.03	0.83	112	2.9%	7.02
Average	1.00	0.83	108	3.0%	7.22

In Figure 3 the slopes of the cumulative energy correspond to the power draw. Correspondingly, the lowest slope (least power used) is the slow ASD, then fast ASD, then semiprofessional heat pump dryer[1], then a semi-professional electric resistance dryer[2], and finally a standard conventional electric resistance dryer[3]. Note that the cumulative energy used is also in the same ordering as the power draw (slope).

1 This standard European heat pump clothes dryer costs approximately $3,500, significantly more than the ASD heat pump dryer.
2 Although this model is listed as a residential electric clothes dryer, it costs significantly more than the average electric resistance clothes dryer sold in the United States – approximately $1500.
3 This is a newer conventional electric resistance dryer sold in the U.S. for approximately $900.

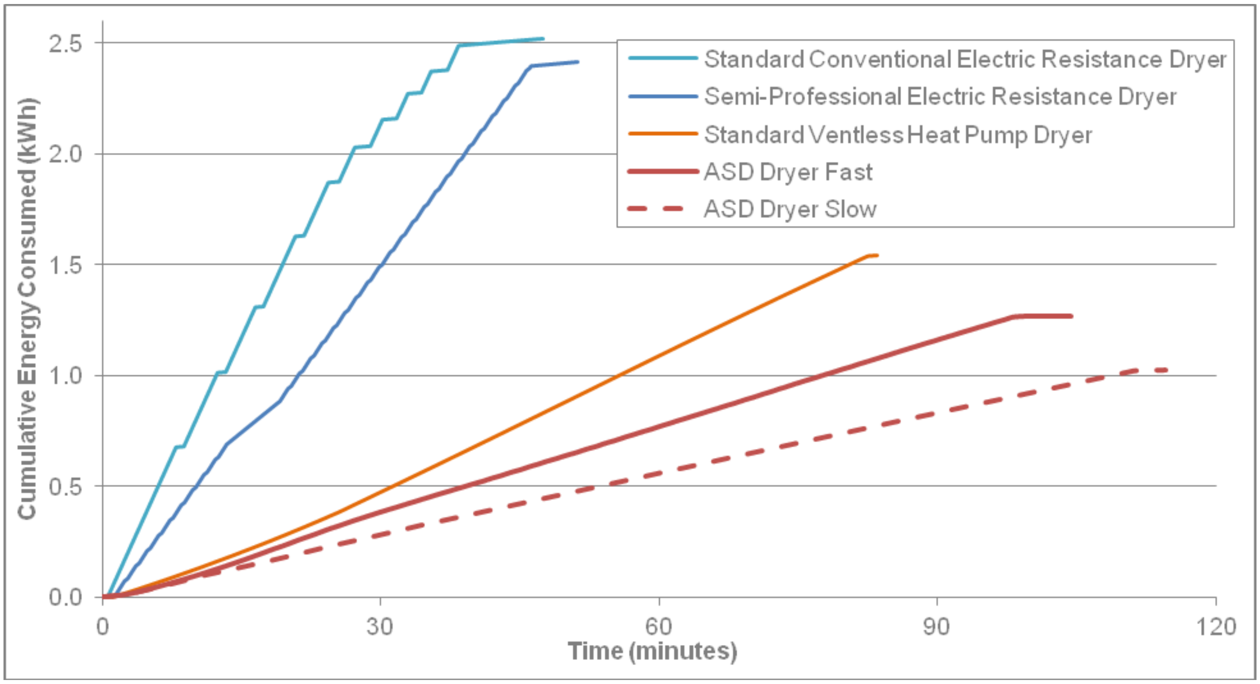

Figure 3. Energy consumption over drying time for ASD dryer vs. heat pump and electric resistance dryers.

As expected, the ASD on fast mode dried more quickly and was less efficient. However, the drying times are still not competitive with conventional electric resistance dryers. The economics of heat pump dryers appear to be favorable in some locations, and they have gained significant market share in Europe. However, the competition in Europe is typically electric resistance condensing dryers, which are less efficient, slower, and more expensive than the vented dryers that are common in the U.S. Therefore, it is not clear that heat pump dryers will become popular in the U.S. If they do, then an ASD can cost effectively allow consumers the ability to save even more energy if they are not in a hurry.

Extrapolating from the dryer tests results obtained, 50% energy savings could be anticipated from 100% market penetration of heat pump ductless clothes dryers which utilize ASD controlled compressors. Therefore energy savings = 3,950 GWh/yr x 0.50 = 1975 GWh/yr.

US DOE estimates each dryer operates 283 dryer cycles per year and testing shows 1.2 kWh savings per cycle which translates to savings of 283 x 1.2kWh = 340 kWh/yr

California has approximately 3,120,000 electric clothes dryers, and assuming 100% market penetration of ductless heat pump dryers in CA the predicted energy savings would be 1,061 GWh/yr.

US DOE estimates a 6% penalty on HVAC systems created by ducted clothes dryers. The use of ductless heat pump dryers will avoid this penalty for anticipated net energy savings.

Ducted HVAC System

Methodology. At the EPRI laboratory, the variable capacity system was tested at high, intermediate, and low compressor speeds. The total capacity, latent capacity, and efficiency of the two tested systems were compared at and away from SEER conditions. Since the variable capacity system could operate at three compressor speed levels, the systems were mostly compared with similar sensible capacity loads. At standard AHRI testing conditions, an indoor temperature of 80°F dry bulb and 67°F wet bulb and an outdoor temperature of 95°F, the variable capacity system at high compressor speed demonstrated an efficiency increase of 11.1% and a dehumidification decrease of 13.4% when compared to the single speed system. Away from standard conditions at an indoor temperature of 75°F dry bulb and 63°F wet bulb and an outdoor temperature of 85°F, the variable capacity system at low compressor speed demonstrated an efficiency increase of 12.5% and a dehumidification decrease of 53.8% when compared to the single speed system. Higher efficiency within the variable capacity system was in part due to a larger heat exchanger coil size within the system. At part load conditions, the ability of the variable capacity system to operate at a decreased compressor speed and maintain full use of the heat exchanger surface also allowed for increased efficiency. Lower dehumidification within the variable capacity system was due to a higher airflow rate per amount of capacity output and an increased operating evaporator temperature.

A single speed and adjustable speed heat pump were tested under identical conditions. Both systems were air-source, ducted systems rated at a nominal capacity of two tons. The systems were examined at 80°F dry bulb and 67°F wet bulb and a varied outdoor temperature.

Results. The testing determined that the single speed system consumes 1,482 kWh/yr and the ASD system consumes 949 kWh/yr so an annual energy consumption savings of 36% (533 kWh) was possible.

Extrapolating from the test results obtained, 36% energy savings is anticipated from 100% market penetration of the ASD controlled compressors used in ducted central HVAC equipment. Therefore energy savings = 5,321 GWh/yr x 0.36 = 1,916 GWh/yr. Predicted energy savings of 533kWh/yr from each of 6,500,000 ducted central HVAC in CA is equivalent to savings of 3,465 GWh/yr. Conservatively, energy saving for 100% penetration of ASD controlled compressors in ducted central HVAC systems is estimated to be 1,916 GWh/yr.

Ductless Single Room HVAC System

Methodology. A ductless heat pump, mini-split system was compared to a window unit using performance data from NREL.

Results. A potential of 54% energy savings is anticipated from 100% market penetration of the ASD controlled compressors used in ductless single room HVAC equipment. Therefore energy savings = 351 GWh/yr x 0.54 = 190 GWh/yr with predicted energy savings of 624kWh/yr from each of 1,950,000 ductless single room HVAC equipment in CA is equivalent to 1,267GWh/yr.

Conservatively, energy savings for 100% penetration of ASD controlled compressors in ductless single room HVAC equipment is estimated to be 190 GWh/yr.

Summary of Testing Results

The predicted results are of such a wide range that further investigation is warranted. Market projections and test results are summarized in the two tables below. These results represent the potential energy savings that may be anticipated from the use of ASD controlled compressors. Further energy savings can be achieved for each application by using speed control of fans.

An investigation of the introduction of fan control in a refrigerator/freezer application indicated further savings of 1,200 GWh/yr could be achieved.

The ductless clothes dryer would yield a further 6% savings on HVAC costs equivalent to 5,321 GWh/yr x 0.06 = 319 GWh/yr as conditioned air would no longer be wasted.

Table 2. Summary of market projections

Appliance	CA Units (M)	Market Projection Energy Use (GWh/yr)	Market Projection Savings
Refrigerator/Freezer	18.4	15,787	6,237 GWh/y
Ductless Clothes Dryer	3.1	3,950	1,105 GWh/y
Central Ducted HVAC	6.5	5,321	2,607 GWh/y
Ductless Room HVAC	1.9	351	142 GWh/y

Table 3. Summary of test results

Appliance	CA Units (M)	Unit Savings Prediction (% or kWh/yr)	Annual Savings Prediction
Refrigerator/Freezer	18.4	19.6% or 328 kWh/y	3,094 GWh/y
Ductless Clothes Dryer	3.1	50% or 340 kWh/y	1,061 GWh/y
Central Ducted HVAC	6.5	36% or 533 kWh/y	3,465 GWh/y
Ductless Room HVAC	1.9	54% or 624 kWh/y	1,267 GWh/y

Conclusion

Adjustable speed control in domestic appliances offers a variety of benefits that are attractive in terms of energy savings, and the environment. In general operating costs are lower, energy is saved, there is less operating noise, component life is extended, and the environmental impact is reduced; consumers experience palpable reward. They save energy, save money, and experience lower levels of appliance noise.

The major benefit achieved thus far is from speed control of compressors within appliances; this equipment design modification typically offers 20% energy savings. The latest refrigerator/freezers provide these benefits.

Heating and cooling systems, both ducted central and ductless single room HVAC, using speed control show a marked improvement in performance. Like the refrigerator/freezer, energy is saved, noise is reduced, and environmental benefits accrue. Less noise equates to better room and building comfort. With respect to single room HVAC systems the ductless design is impressively quiet and completely dissimilar to its older counterpart; it offers comfort from whisper quiet noise levels. These are tangible advantages to be gained. Temperature excursions are reduced and comfort levels are improved. Humidity control becomes much tighter because stop/start features are replaced with a ramped condition change. Reduced operating cycles in the compressor will increase compressor life by 40%. Motor life doubles. Temperature levels improve 10°C or more. Higher speed available from the ASD controlled compressor improves heat pump performance. There is potential for further improvement; ECMs fitted on evaporator and condenser fans will provide greater noise reduction and further energy savings. The availability of demand response offers remote monitoring and control that helps plan energy use at peak times.

Ductless clothes dryers that use a heat pump save 50% of electrical energy and save 6% of HVAC energy costs; conditioned air remains in the building rather than exhausted as takes place with a conventional ducted dryer. A ductless dryer can be placed anywhere. It does not release humidity into the air and produces no lint.

References

California Energy Commission (CEC). 2014. *Consumer Electronics and Motorized Appliances*. Prepared by the Electric Power Research Institute (EPRI). PEIR Project #500-10-022. Sacramento, CA.