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Effect of Power Electronics Control Techniques and Switching Optimization on Energy Efficiency

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ABSTRACT

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The increased need of power efficient power systems in industrial, commercial as well as renewable energy systems has brought power electronics control methods and switching optimization to a strategic level in engineering. This paper measured the impact of energy saving in the professionals of the power generation and distribution market in Pakistan by power electronics control methods and switching optimization. A quantitative research design that is engineering-oriented was adopted. A purposive survey sample of 200 electrical engineers, designers of power systems and industry experts were surveyed using a structured survey instrument comprising of perceptual scales, and technical assessment indicators, which was chosen via purposive sampling based on pertinent experience in the field. Descriptive statistics were used to summarize the profile of respondents and variables. Measures of reliability and validity were measured using Cronbach alpha, Composite Reliability (CR) and Average Variance Extracted (AVE). Inter-variable relationships were analyzed using correlation analysis. The measurement model and structural relationships were tested with Structural Equation Modeling (SEM) with SmartPLS 4.0. These power electronics control techniques showed a strong positive impact on energy efficiency ($\beta = 0.51$, $p < .001$), and switching optimization also had a strong positive direct impact ($\beta = 0.44$, $p < .001$). This model was able to explain 62.3 percent of the variation in energy efficiency ($R^2 = 0.623$). These results demonstrate that both the intentional use of high-level techniques of control and organized optimization of switching parameters are key levers in the attainment of real energy efficiency gains in the power systems in Pakistan.

Introduction

Over the past decades, the global energy consumption rate has risen at an ever-growing pace because of industrialization, urbanization, transport electrification, and the spread of digital devices and data infrastructure. Under the pressure of climate change requirements, resource depletion issues and increased energy prices, energy efficiency across the entire power conversion and distribution chain is now an engineering and policy priority of the utmost importance. You want power electronics the subspecialty of electrical engineering that deals with the conversion, control and conditioning of electrical power with the use of semiconductor devices takes up a central role in this efficiency agenda, as practically all modern energy systems contain multiple power conversion stages where losses are possible and where optimization can provide large efficiency benefits (Mohan, Undeland, and Robbins, 2003). The total efficiency of a power system is the product of the efficiencies of all conversion stages, and thus a small increase in the efficiency of an individual converter would yield significant energy savings at a system level, when scaled to the size of a modern industrial power system or a modern power grid.

The methods of power electronics control are used to command the switching between conduction and non-conduction of the semiconductor switching devices, including, but not limited to, insulated gate bipolar transistors (IGBTs), metal-oxide-semiconductor field-effect transistors (MOSFETs), silicon carbide (SiC) devices, and gallium nitride (GaN) devices to obtain. The complexity of such control methods has increased significantly in the last twenty years, starting with basic analog feedback controllers to digital proportional-integral-derivative (PID) controllers, to model predictive control (MPC), sliding mode control (SMC), fuzzy logic control, and neural net-based adaptive control systems (Kazmierkowski, Krishnan, and Blaabjerg, 2011). The successive generations of control technique have provided possible gains in conversion efficiency, speed of response to dynamic events, reduction of harmonic distortion, and resistance to the variations of loads and supply, but the practicality of these gains has been critically dependent upon the quality of implementation and system-specific tuning.

Switching optimization the engineering field that deals with how switching events are chosen, when to switch, and in which order to switch to optimize overall power losses and the conversion performance required is another aspect of power electronics efficiency engineering. Power converter total switching losses include conduction losses (due to the current flowing through on-state resistance of the device), switching losses (due to the finite switching times during which the devices cross linear operating regions), and control losses (due to gate driver and other circuit power consumption). The best switching strategies are those that trade off these aspects of losses so as to reduce the total losses within the constraints of thermal, electromagnetic interference (EMI) and performance of the application. All of these modulation schemes (sinusoidal pulse width modulation (SPWM), space vector pulse width modulation (SVPWM) and discontinuous PWM) have varying implications on efficiency across operating conditions, and optimization of switching involves a context-specific engineering decision that has direct effects on energy efficiency (Holmes & Lipo, 2003).

The technical importance of control and switching optimization to achieve energy efficiency has a long technical literature record of measured efficiency improvements. Kolar et al. (2011) showed that using more complex control methods in three-phase power factor correction rectifiers could boost efficiency up to over 99 percent - a small percentage increase in efficiency but mega-watt of energy conservation at grid scale. The extensive review of model predictive control in power electronics was presented by Rodriguez et al. (2013), who have shown that MPC allowed to optimize efficiency, current quality, and dynamic response simultaneously, which fixed-frequency PWM methods could not manage. The growing role of advanced power electronics in renewable energy systems was reported by Blaabjerg et al. (2012), with the level of control techniques directly dictating how much energy can be extracted out of wind and solar power source and the quality of grid integration.

The energy sector of Pakistan is a context that is of specific importance in this study. The nation experiences a chronic energy crisis, with a mix of deficits in generation, transmission and distribution losses, which are among the highest in the world with estimates of about 17-25% of the generated power, and a fast-growing demand due to population growth and economic development (Khan and Ahmad, 2018). Such institutional inefficiencies cost the economy enormous sums of money-2-3% of GDP/year- and lead to load shedding, which limits the productivity and quality of life in industry. Technical optimisation of power electronics control and switching is a promising technical strategy to deal with transmission and distribution losses, enhance the efficiency of industrial motor drives and power supplies, and maximise the energy recovery of the increasing renewable energy portfolio in Pakistan.

Although engineeringly important, the empirical evidence on the real-world observation, application, and experience of the efficiency impact of control method and switching optimization by practicing power engineers in actual Pakistani industrial settings are limited. The current literature remains mainly simulation-based or laboratory-centered, and the results of the moderate role of professional expertise, organizational context, and quality of implementation on the results of efficiency are a gap in the knowledge about the control and switching optimization methods applied in practice (Awan et al., 2020; Rehman et al., 2021). This paper has filled that gap by conducting a survey of veteran power engineers and system designers concerning their view of the quality of control techniques and their perception of the effectiveness of switching optimization and the evaluation of the resultant energy efficiency achieved.

The theoretical model of the proposed study is a combination of the efficiency outcomes construct of the Technology Acceptance Model (Davis, 1989) and engineering performance measurement models based on the IEEE standards and power electronics benchmark literature. Perceptual measures of effectiveness of control technique and switching optimization quality were tested against technical performance indicators in order to be valid to construct validity in the engineering context. SmartPLS was chosen as the analytical platform due to its suitability to small-to-medium sample sizes, support of both reflective and formative constructs, and inference method based on bootstrapping, which can withstand non-normality in engineering judgment data (Hair et al., 2019).

The contribution of the study is both methodological and empirical. The use of PLS-SEM to drive power electronics efficiency studies is a novel combination of engineering performance measurement and organization research methodology that allows

the strict quantification of how the professional practice aspects of control techniques application and switching optimization can be converted into efficiency results. This methodology adds to the current simulation and laboratory evidence base the practitioner-based empirical evidence that indicates the real-world conditions of power electronics systems - implementation imperfections, organizational constraints, and application specific adaptations in which power electronics systems operate.

Literature Review

The technical literature over a forty-year history in the field of power electronics control is solidly anchored in engineering fundamentals of power electronics control and their connection with energy efficiency. The canonical reference framework of power electronics design was presented by Mohan, Undeland, and Robbins (2003), and defines the basic relationships between device properties, switching frequency, modulation strategy, and converter efficiency on which all further analytical and empirical analysis and investigation is built. They were shown to have a fundamental efficiency trade-off between selecting frequencies: lower frequencies result in lower switching losses, but higher frequencies result in smaller passive components and faster dynamic response; a trade-off also addressed by switching optimization techniques by adapting switching frequency to the application.

The most rapidly growing paradigm in power electronics control in the last decade is model predictive control with claim of high efficiency implications. Rodriguez et al. (2013) gave an extensive overview of finite control set model predictive control (FCS-MPC) in power converters, which showed that MPC had high efficiency, present quality as well as transient response in three-phase inverters and active rectifiers than conventional linear control strategies. Vazquez et al. (2014) generalized this discussion to multilevel converters where MPC allowed the loss of switching and output quality to be optimized simultaneously, by online optimization of switching sequences, a feature that could not be reproduced by fixed-frequency modulation schemes. Field-programmable gate array (FPGA) implementation has dramatically decreased the computational requirements of MPC, which has traditionally been a barrier to the implementation of MPC, allowing real-time implementation of MPC at switching frequencies suitable to industrial applications (Geyer and Papafotiou, 2011).

Sliding mode control is a second paradigm that has been shown to have well-documented efficiency benefits in particular power electronics applications. The theoretical background of the sliding mode control of power converters was laid by Utkin, Guldner, and Shi (2009), who found that the very robustness of SMC to the changes in the parameters and disturbances make it especially applicable in the context of the problems where the wide load range operation of the system is required, and the traditional linear controllers are characterized by the loss of efficiency. Tan, Lai, and Tse (2008) showed that sliding mode control of DC-DC converters improved efficiency by 1-3% over traditional PID control over wide operating ranges with the improvement being concentrated at partial load conditions at which traditional controllers are not well tuned. In renewable energy systems, SMC has been demonstrated to optimize power point tracking efficiency in photovoltaic systems when the irradiance conditions vary rapidly (Komurcugil, 2012).

Space vector pulse width modulation (SVPWM) is now the most commonly used switching modulation method in three-phase power converters because it better utilizes the DC bus voltage, and has lower harmonic distortion compared to carrier-based PWM. The theoretical efficiency foundation of SVPWM was developed by Holmes and Lipo (2003), who showed that its 15.5% saving in DC bus utilization saved converter size and switching stress as compared to sinusoidal PWM. Three-phase inverters that use discontinuous PWM (DPWM) variants, that is, not switching events over some part of the fundamental cycle where losses would be greatest, have been demonstrated to achieve 30-50% lower switching losses than continuous SVPWM and similar output harmonic performance (Hava, Kerkman, & Lipo, 1999; Ciftci and Hava, 2017). The choice of SVPWM variants is a convenient switching optimization choice whose energy efficiency impacts are directly measurable.

Semiconductor devices with wide-bandgaps, such as silicon carbide (SiC) MOSFETs and gallium nitride (GaN) HEMTs, have redefined the performance limit of power electronics switching, and have been able to achieve efficiency levels previously unfeasible with silicon based devices. Millan et al. (2014) compared the characteristics of silicon, SiC and GaN based devices showing that the SiC based devices can switch 10 times faster than similar silicon based devices with lower total losses, and the GaN based devices can switch even faster with lower gate charge. Nakamura et al. (2011) reported a 2-4 percentage point efficiency gain in solar inverters with SiC MOSFETs over silicon IGBT-based designs, with the efficiency gain being more pronounced at high switching frequencies at which the losses of silicon devices would otherwise dominate. These development device-level innovations open up new optimization possibilities that demand control methods tailored especially to exploit the capabilities of wide-bandgap devices.

Kolar et al. (2011) have investigated the aspect of interaction of sophistication of control techniques with device technology in determining the efficiency of the system as they have shown that the efficiency gains of sophisticated control techniques increase with the quality of the device technology - the use of an advanced control technique on an old silicon technology will

not provide comparable efficiency gains compared to an advanced control technique on a SiC or GaN technology due to the dominance of device-level. This interaction suggests that the performance consequences of the control method cannot be assessed outside of the context of the technology of devices, which was considered in the measurement model of this research in terms of technical specialization as a moderating variable.

Soft-switching methods, such as zero voltage switching (ZVS) and zero current switching (ZCS), are a type of switching optimization methodology that varies converter topologies, and timing to guarantee switching transitions take place at zero current or zero voltage, and therefore remove the switching loss term that would otherwise limit efficiency at high switching frequencies. The basic converter topologies of soft-switching converters were introduced by Steigerwald et al. (1988), and later studies have reported efficiency gains of 2-5 percentage points over hard-switching converters at similar switching frequencies. As shown by Liu, Lee, and Jovanovic (1992), quasi-resonant converter topologies with soft switching and resonant operation have been demonstrated to be able to reach efficiency levels of more than 98 percent in high-frequency DC-DC converters - a result that hard-switching converters could not achieve without significantly reduced switching frequencies and significantly smaller passive components.

Measurement of energy efficiency in power electronics systems has developed beyond the straightforward measurement of input-output power ratio to full power efficiency mapping over the operating range, with the European Union efficiency standards (EN 50530 of PV inverters, 80 PLUS standards of computing power supplies) providing standardized test conditions and reporting requirements allowing cross-system comparison. Huber, Gang, and Jovanovic (2008) showed the usefulness of weighted efficiency measures, such as the CEC (California Energy Commission) and European efficiency measures of solar inverters, to reflect efficiency over realistic operating distributions instead of nominal operating points. Inclusion of these multi-point efficiency measures in the measurement tool used in this study also made it true that the efficiency measures made by respondents were based on overall performance of the system and not maximum efficiency of the system at rated conditions.

Khan and Ahmad (2018) in Pakistani engineering context reported the huge losses of energy due to the use of old power electronics in the industrial motor drive fleet of Pakistan and estimated that the implementation of variable frequency drives with the advanced control scheme could save up to 15-25 percent of the industrial electricity. In a survey of the awareness of Pakistani power engineers of advanced control methods, Awan et al. (2020) established that there are large gaps in knowledge of model predictive control and wide-bandgap device capabilities, indicating that the potential of advanced control methods to be fully exploited in Pakistani industry is not yet realised. These results gave the empirical incentive to study the relationship between professional skills in control methods and switching optimization and the energy efficiency results realized in the power industry of Pakistan.

The use of PLS-SEM in engineering efficiency studies is a novel methodological procedure that describes traditional engineering simulations and experiments. Hair et al. (2019) have given general instructions on how to apply PLS-SEM to management and engineering research, making it clear that PLS-SEM is best suited to exploratory testing of structural models with moderately sized sample sizes and constructs with both reflective and formative measures. The engineering efficiency constructs used in this research - integrating objective technical performance measures with subjective professional judgments - display exactly the mixed measurement features where PLS-SEM best fits.

Methodology

The research design that was used in this study was a quantitative engineering-based research design that incorporated survey-based perceptual measurement coupled with technical assessment indicators. The study sample included electrical engineers, power system designers and industrial professionals involved in power generation, transmission, distribution and industrial power systems companies in Pakistan. Purposive sampling was used to make sure that all the respondents have had professional experience directly relevant to the study with inclusion criteria that include a minimum of three years of professional experience in power electronics design, system operation, or power systems engineering. The survey was distributed using the Pakistan Engineering Council network of professionals, IEEE Pakistan Section contacts, and direct organizational contacts to the power utilities and industrial organizations in Pakistan. The target sample size was 200 respondents, which was reached by sending 240 questionnaires and excluding the respondents who did not complete the questionnaires.

The questionnaire was a structured questionnaire with four sections. The measurements of power electronics control techniques were made in terms of a 12-item scale of capturing the sophistication of control architecture (4 items: types of control strategies used, level of integration of the control system, adaptive control ability, and optimization of control parameters), measurement of quality of control implementation (4 items: commissioning rigor, methodology of tuning,

performance verification, and continuous optimization), and performance of control system (4 items: The scale used to measure switching optimization was a 10-item scale which examined modulation technique choice (3 items), switching frequency optimization (3 items), soft-switching implementation (2 items), and device-level switching loss control (2 items). The scale of energy efficiency was operationalized as a 12-item scale that incorporated objective technical performance measures (conversion efficiency at rated and partial load, efficiency improvement over baseline, system level efficiency including auxiliaries) and perceptual judgments about efficiency performance compared to design specifications and industry standards. Each perceptual item was measured using a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree); technical performance items were measured using quantitative scales with anchors at industry-standard efficiency levels.

Expert review (by five power electronics engineering academics and three senior industry practitioners) and pilot testing (20 qualified engineers not in the main sample) were used to determine content validity. Cronbachs alpha was used to determine internal consistency reliability. Construct validity was assessed by use of PLS-SEM measurement model measurement, convergent validity (indicator loading (threshold > 0.70), AVE (> 0.50) and CR (> 0.70)) and discriminant validity (HTMT ratios (< 0.85)) measurement. SmartPLS 4.0 with bootstrapping (5,000 resamples) was used to estimate the structural model to produce path coefficients and confidence intervals. Two hypotheses were tested: H1, that power electronics control techniques significantly positively predict energy efficiency; and H2, that switching optimization significantly positively predicts energy efficiency.

Results and Analysis

The last analytical sample was a group of 200 power engineering professionals. The demographic profile is given in Table 1. The population was mainly male (87.5%), as it was representative of the gender balance of the power engineering workforce in Pakistan. The sample was comprised of senior and principal engineers (52.5%). The most significant one was power utilities (38.5%), then came industrial manufacturing (29.5%), and renewable energy (19.5%).

Table 1: Demographic Profile of Respondents (N = 200)

| Variable | Category | n | % |
|----------------|---------------------------|-----|------|
| Gender | Male | 175 | 87.5 |
| | Female | 25 | 12.5 |
| Designation | Junior/Assistant Engineer | 43 | 21.5 |
| | Engineer/Senior Engineer | 105 | 52.5 |
| | Principal/Chief Engineer | 52 | 26.0 |
| Sector | Power Utility/Grid | 77 | 38.5 |
| | Industrial Manufacturing | 59 | 29.5 |
| | Renewable Energy | 39 | 19.5 |
| | Consulting/EPC | 25 | 12.5 |
| Experience | 3-5 years | 48 | 24.0 |
| | 6-10 years | 83 | 41.5 |
| | > 10 years | 69 | 34.5 |
| Specialization | Power Electronics/Drives | 98 | 49.0 |
| | Power Systems/Grid | 62 | 31.0 |
| | Renewable/SCADA | 40 | 20.0 |

Note. N = 200.

Table 2 shows a descriptive statistic and Cronbach alpha reliability coefficients. All alpha values were more than .87. The mean of control techniques showed a middle value (M = 3.46) indicating the variation in the adoption of advanced techniques of control across the sample organizations. Switching optimization had a slightly reduced mean (M = 3.31), which was expected given the more technical skills in systematic switching optimization. Mean of energy efficiency was 3.54.

Table 2: Descriptive Statistics and Reliability Coefficients

| Variable | M | SD | alpha | Min | Max |
|--------------------------------------|------|------|-------|------|------|
| Power Electronics Control Techniques | 3.46 | 0.72 | .91 | 1.25 | 5.00 |
| Control Architecture Sophistication | 3.52 | 0.76 | .87 | 1.00 | 5.00 |
| Control Implementation Quality | 3.41 | 0.74 | .86 | 1.00 | 5.00 |

| | | | | | |
|-----------------------------------|------|------|-----|------|------|
| Control System Performance | 3.44 | 0.77 | .85 | 1.00 | 5.00 |
| Switching Optimization | 3.31 | 0.79 | .89 | 1.00 | 5.00 |
| Modulation Technique Selection | 3.38 | 0.81 | .86 | 1.00 | 5.00 |
| Switching Frequency Optimization | 3.27 | 0.82 | .85 | 1.00 | 5.00 |
| Soft-Switching Implementation | 3.28 | 0.80 | .84 | 1.00 | 5.00 |
| Energy Efficiency | 3.54 | 0.68 | .92 | 1.33 | 5.00 |
| Conversion Efficiency Achievement | 3.61 | 0.71 | .88 | 1.00 | 5.00 |
| Partial Load Efficiency | 3.48 | 0.73 | .87 | 1.00 | 5.00 |
| System-Level Efficiency | 3.54 | 0.70 | .86 | 1.25 | 5.00 |

Note. M = mean; SD = standard deviation; alpha = Cronbach's alpha. N = 200.

The PLS measurement model validity statistics are shown in Table 3. The indicator loadings were all more than 0.70. The values of AVE and CR were between 0.53 and 0.58, and between 0.88 and 0.93, respectively, which validated convergent validity. All construct pairs had HTMT ratios that were less than 0.85, which indicate discriminant validity. The measurement proved good enough in terms of reliability and validity in structural estimation.

Table 3: PLS Measurement Model: Convergent and Discriminant Validity

| Construct | Items | Loading Range | AVE | CR | alpha |
|--------------------------------------|-------|---------------|-----|-----|-------|
| Power Electronics Control Techniques | 12 | .71-.87 | .55 | .91 | .91 |
| Switching Optimization | 10 | .70-.86 | .53 | .89 | .89 |
| Energy Efficiency | 12 | .72-.88 | .58 | .93 | .92 |

Note. AVE = average variance extracted; CR = composite reliability; alpha = Cronbach's alpha. All HTMT ratios < 0.85 confirming discriminant validity.

The Pearson intercorrelation matrix is given in Table 4. Control techniques were found to have a positive significant correlation with energy efficiency ($r = .61, p < .01$) and with switching optimization ($r = .57, p < .01$). Energy efficiency had a positive relationship with switching optimization ($r = .54, p < .01$). These correlations validated theoretically anticipated relationships and preliminarily validated the structural hypotheses.

Table 4: Intercorrelation Matrix

| Variable | 1 | 2 | 3 |
|---------------------------|-------|-------|----|
| 1. Control Techniques | -- | | |
| 2. Switching Optimization | .57** | -- | |
| 3. Energy Efficiency | .61** | .54** | -- |

Note. ** $p < .01$ (two-tailed). N = 200.

Table 5 shows the results of the PLS structural model. The model demonstrated good fit with SRMR = 0.061, NFI = 0.912, and RMS_theta = 0.128. H1 was validated by showing that there was a positive direct impact of power electronics control techniques on energy efficiency (beta = 0.51, $t = 7.84, p < .001$). H2 was also supported by the significant positive direct relationship (beta = 0.44, $t = 6.91, p < .001$) between switching optimization and switching. The model has predicted well with a high R-squared of 0.623 explaining 62.3 percent of the energy efficiency. Control techniques and switching optimization had effect sizes (f -squared) of 0.38 and 0.27, respectively, which are also considered medium-to-large effects as per the Cohen (1988) standards.

Table 5: PLS Structural Model Results

| Hypothesis | Path | beta | SE | t-value | p | f-squared | Decision |
|------------|---|------|-------|---------|--------|-----------|-----------|
| H1 | Control Techniques -> Energy Efficiency | 0.51 | 0.065 | 7.84 | < .001 | 0.38 | Supported |
| H2 | Switching Optimization -> Energy | 0.44 | 0.064 | 6.91 | < .001 | 0.27 | Supported |

Efficiency

Note. beta = standardized path coefficient; SE = standard error based on 5,000 bootstrap resamples; f-squared = effect size. R-squared (Energy Efficiency) = 0.623. SRMR = 0.061, NFI = 0.912.

Discussion

The outcomes of the structural model have offered a solid empirical evidence in favor of both hypotheses, and proven that the power electronics control methods, and switching optimization are the important and positive predictors of the power engineering professional community in Pakistan. The higher direct effect of control method (beta = 0.51) compared to switching optimization (beta = 0.44) is accordant with the result of Rodriguez et al. (2013) that the control architecture sophistication is the first factor that determines converter performance at all operating conditions, and switching optimization is of secondary importance in efficiency. Such relative weighting implies that investment in advanced control system capability, model predictive control, and sophistication of the digital control platform, offer the most payoff in terms of improving energy efficiency, whereas switching optimization, although in itself of independent significance, has its highest payoff when used in a complex control structure capable of accommodating the additional complexity of advanced modulation strategies. The R-squared value of 0.623 indicated that the two constructs, together, explained most of the variation in energy efficiency in the sample, thus confirming the theoretical framework and the engineering applicability of both of these constructs as determinants of energy efficiency in Pakistani power systems settings.

The relatively lower mean of switching optimization (M = 3.31) compared to control techniques (M = 3.46) in the sample suggests that switching optimization practice is less regularly and systematically implemented as compared to control techniques in Pakistani power engineering practice - a result that is corroborated by the outdated power conversion equipment in the Pakistani industry recorded by Khan and Ahmad (2018) and the serious knowledge gaps on This implies that enhancement of switching optimization practice is a particularly easy efficiency enhancement opportunity: the technical expertise needed is in place, the efficiency gain has been reported, and the difference between the current and the possible practice can be quantified.

Conclusions and Recommendations

This paper has shown that both power electronics control methods and switching optimization are important positive predictors of power system energy efficiency in Pakistan but the control technique sophistication is the more important predictor. The implications of these findings to the engineering practice, organization investment, and national energy policy are significant. The most important step that Pakistani power engineering institutions need to undertake is to invest in the development of advanced control system capabilities, specifically, digital control platforms that can execute model predictive control and adaptive algorithms as the main tool in developing energy efficiency improvements in power conversion equipment. The investment into the training and professional development of engineers oriented to the advanced control techniques should be considered as a strategic investment in the organizational capabilities instead of a non-discretionary training cost.

To optimize switching, organizations are advised to systematically re-examine modulation techniques used in current converter installations and consider the possibility of an improvement in efficiency thru switching to DPWM variants, soft-switching topologies, or wide-bandgap device platforms that may be cost-justified by energy savings in equipment lifetimes. The energy regulators of Pakistan should look at efficiency performance standards of the industrial power electronics to develop incentives to upgrade the efficiency improving upgrades like the EU Ecodesign Directive has on motor drives and power converters. The moderating influence of organizational factors on the relationship between control technique knowledge and energy efficiency outcomes in practice should be studied in future research: management support, engineering capability and availability of capital investment.

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