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Hybrid Machine Intelligent SVR Variants for Wind Forecasting and Ramp Events

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Abstract

Wind speed and power forecast is an essential component to ensure grid stability and reliability. The traditional forecasting methods fail to address the non-linearity in the wind speed time-series, thus paving way for machine intelligent algorithms. This paper discusses a hybrid machine intelligent wind forecasting model utilizing different variants of Support Vector Regression (SVR) built on wavelet transform. Various performance indices are evaluated to identify the possible best one among four different machine learning regressors for wind forecasting application. Apart from standard ε -SVR and LS-SVR, two new regression models, namely, ε -Twin Support vector regression (ε -TSVR) and Twin Support vector regression (TSVR) are used to forecast short-term wind speed, and are compared with Persistence model for four wind farm sites. The effect of larger dataset on forecasting performance is evaluated for two wind farm sites from USA and India. Further, wind power ramp events are investigated at different hub heights and the forecasting performance of different variants of SVR is compared for five wind farm sites.

Keywords: Wind forecasting, Wavelet transform, Twin Support vector regression, ε -Twin Support vector regression, Wind power ramp events

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1. Introduction

Growing wind energy potential is attracting investments in the renewable energy market. With abundant wind availability, tapping power from wind is important. The demand for energy has pushed the envelope for renewable energy technologies, and Solar, wind, biomass being the pioneers, many developing countries are now focusing on utilizing the sustainable sources of energy. Wind energy brings a balance in the ecosystem by compensating the carbon footprints created by thermal power plants. Globally, wind energy brings job opportunities particularly in operations and maintenance (O&M) sector. According to Global wind energy council (GWEC) report [1], in 2017, with an installed capacity of 2.08 GW, wind sector in South Africa created 15,000 jobs while in Europe a total of 262,712 jobs were created. Lucrative tariff rates have ensured support for wind technology, both onshore and offshore.

Despite numerous advantages, wind sector leads to an imbalance in aquatic life, high initial investment costs and procedural obstacles in land acquisition. But, advanced manufacturing technologies have opened doors for rapid wind energy installations, and wind regime for offshore sites is found much stronger than onshore ones, which motivates investors to participate in bidding process. Threats posed by wind turbines include bird killings, high noise levels, opposition from local communities including farmers concerned about their livestock. Wind farms are being constructed keeping in mind the space constraints and recently a lot of focus is fed on Savonius style wind turbines (SSWT) operating under any wind direction. Roy et al. have discussed an inverse method based on differential evolution for determining optimal turbine dimensions [2]. Results reveal that area of SSWT is reduced by 9.8%. Further, a 2D computational fluid dynamics model is put forward by Gupta and Biswas to evaluate the steady state performance of a twisted three-bladed H-Darrieus rotor [3]. Considering wind as a stochastic variable, its accurate prediction can yield benefits to the plant operators. However, the error processing of forecasted wind speed/power and actual wind speed/power plays a crucial role in selecting appropriate forecast-

31 ing algorithms. Machine learning models like Artificial neural networks (ANN),
32 Support vector regression (SVR) [4]-[5], Gaussian process regression (GPR),
33 Fuzzy logic and Extreme learning machine are widely used.

34 Recently a lot of impetus has been laid on hybrid wind forecasting that in-
35 corporates the advantageous aspects of individual methods. Earlier works in the
36 field of hybrid wind forecasting include ARIMA-ANN model developed by Can-
37 denas and Rivera where for a fixed prediction horizon, wind forecasting is done
38 [6]. Liu et al. have described a Support vector machine and Genetic algorithm
39 (GA) based hybrid short-term forecasting technique using Wavelet transform
40 for the decomposition of the wind signal and removal of any stochastic vari-
41 ations [7]. Zhang et al. have proposed a hybrid method based on gaussian
42 process regression (GPR) and auto-regression (AR) and compared their wind
43 speed forecast with results obtained through ANN, SVM and persistence mod-
44 els [8]. Mi et al. have described a hybrid model employing wavelet transform,
45 extreme learning machine and outlier correction method to predict multi-step
46 wind speed [9]. Wavelet and wavelet packet decomposition removes noise com-
47 ponent from the wind series and extreme learning machine provides multi-step
48 forecast on the sub-layers obtained in decomposition process.

49 Li et al. have discussed combined models based on variable weight and
50 constant weight for short-term wind speed forecasting [10]. Jiang et al. have
51 proposed a hybrid model employing fluctuations of adjacent wind turbines on
52 target wind turbine and the relevant inputs are fed to the v-SVM model for
53 forecasting short-term wind speed [11]. Azimi et al. have used data mining
54 and wavelet analysis to perform k-means cluster selection of significant features
55 from wind speed time series and the forecast is done using multilayer percep-
56 tron neural network (MLPNN) [12]. Jiang et al. have proposed correlation-
57 aided discrete wavelet transform (DWT), least-square support vector machine
58 (LSSVM) and generalized autoregressive conditional heteroscedastic (GARCH)
59 model. The DWT is carried out to decompose original wind series into sub-
60 series and a correlation coefficient is calculated between each sub-series and

61 original dataset to select inputs for LSSVM model [13]. Further, a multi-step
62 forecasting model based on a hybrid structure involving a modified BFGS neu-
63 ral network and wavelet decomposition based post processing technique is built
64 by Liu et al. and is validated for four wind speed time series [14]. The ef-
65 fectiveness of wavelet filter based decomposition is observed by analyzing the
66 cross-correlation coefficients between the instantaneous frequency components
67 of sub-series. Tian et al. have proposed a hybrid preprocessing and satin bower-
68 bird based multi-objective forecasting algorithm [15] wherein data preprocessing
69 is based on complementary ensemble empirical mode decomposition (EEMD),
70 sample entropy and variational mode decomposition. The proposed method
71 is validated for eight datasets and is found to be superior to the benchmark
72 models, but suffers from large computation time.

73 Wang et al. have implemented a novel hybrid model involving modern drag-
74 onfly algorithm (MODA), an optimization technique to tune the parameters
75 and weights of elman neural network(ENN) to forecast three variables, that is,
76 wind speed, electricity price and electrical load [16]. In order to remove noise
77 and non-linear components from the wind speed time series, several decompo-
78 sition algorithms like empirical mode decomposition (EMD), wavelet transform
79 (WT) and EEMD are used. On similar grounds, Du et al. carried out multi-
80 step ahead forecasting based on a Whale optimization algorithm-LSSVR model
81 and have applied the same to forecast wind speed, electrical load and electricity
82 price [17]. Six different datasets from China, Australia and Singapore are tested
83 for the proposed approach and are compared with Generalized regression neural
84 network (GRNN) and Back propagation neural network (BPNN). Results reveal
85 that WOA-LSSVR model outperforms GRNN and BPNN models in terms of
86 mean squared error, mean absolute error and mean absolute percentage error.

87 Further, Debanath et al. have presented a ANN model to predict the power
88 and torque coefficients for a three-buck savonius type wind turbine. The model
89 has three inputs: (i) overlap ratio, (ii) tip-speed ratio and (iii) angular veloc-
90 ity [18]. Results reveal that a two-hidden layer ANN outperforms single-layer

91 and three-layer ANN topology. Wang et al. have proposed a newly developed
92 hybrid wavelet neural network (WNN) model based multi-objective sine-cosine
93 algorithm (MOSCA) optimization [16]. The model developed is tested for high
94 accuracy and stability in order to ensure a reliable wind farm operation. Fur-
95 ther, based on WNN-MOSCA model each sub-series is forecasted and a aggre-
96 gated time series is obtained. The proposed WNN-MOSCA model is compared
97 with ARIMA, persistence, WNN and GRNN models. However, the above men-
98 tioned forecasting models consume large computation time which is reduced
99 via a hybrid SVR model and associated variants. Wavelet transform, a special
100 Multi-Resolution Analysis (MRA) technique which fragments the input signal in
101 time-frequency domain, is primarily used for power system transients like power
102 ramp-up and ramp-down events that cause severe system jeopardy [19]. In this
103 paper, we decompose the wind speed time-series signal using daubechies fourth
104 order (db4) wavelet filter which ensures smooth and localized decomposition.

105 The main contribution of this manuscript is a hybrid model for wind fore-
106 casting based on wavelet transform and SVR variants. The hybrid model is
107 then compared with persistence model based on several performance metrics
108 and computation time. Effect of regularization on variants of SVR is assessed
109 to evaluate the best hybrid model in terms of short-term forecasting. Further,
110 wind ramp events are assessed for five wind farm sites under different variants
111 of SVR along with frequency distribution at different hub heights. This pa-
112 per is divided as follows. Section 2 describes various SVR variants and their
113 problem formulation. Further, Section 3 discusses the framework for short-term
114 wind speed forecasting and wind power ramp events. In Section 4, results and
115 discussions are presented followed by Conclusions in Section 5.

116 **2. Support Vector Regression**

117 Support vector regression (SVR) works on the principle of structural risk
118 minimization (SRM) from statistical learning theory [20], [21]. The core idea
119 of the SRM theory is to arrive at a hypotheses h which can yield lowest true

120 error for the unseen and random sample testing data [22]. Apart from SVR, a
 121 universal machine intelligent technique called Artificial neural network (ANN)
 122 with applications in character recognition, image compression and stock market
 123 prediction, is studied [23]. Shirzad et al. have compared the performance of
 124 ANN and SVR to predict the Pipe Burst Rate (PBR) in Water Distribution
 125 Networks (WDNs) [24]. It was observed that ANN is a better predictor than
 126 SVR but cannot be generalized as it is not consistent with physical behavior.
 127 SVR has an advantage over ANN with respect to the number of parameters
 128 involved in training phase. The computation time is another important factor
 129 for carrying out regression analysis.

130 Consider a set of training data (historical data) $(x_1, y_1), (x_2, y_2), \dots, (x_n, y_n) \subset$
 131 $X \times \mathbb{R}$, where X denotes the input feature space of dimension \mathbb{R}^n . Let $Y =$
 132 (y_1, y_2, \dots, y_i) denote the set representing the training output or response, where
 133 $i = 1, 2, \dots, n$ and $y_i \in \mathbb{R}$.

134 2.1. ε -support vector regression

135 ε -SVR aims to find a regressor

$$f(x) = w^T x + b, \text{ with } w \in X, b \in \mathbb{R} \quad (1)$$

136 which represents a linear regression function for prediction, where $x \in X$ is the
 137 input set containing all the features, w is the weight coefficient related to each
 138 input vector x_i and b is the bias term.

139 The aim is to find out $f(x)$ with maximum deviation ε from the respective
 140 feature sets or classes while being as flat as possible. In order to achieve the
 141 flatness of the desired regressor, the square of the norm of weight vector w
 142 needs to be minimized. Thus we can formulate the SVR problem into a convex
 143 optimization problem [25] given as

$$\min \frac{1}{2} \|w\|^2 + C(e^T \chi + e^T \chi^*), \quad (2)$$

$$\text{subject to } y - w^T x - eb \leq e\varepsilon + \chi, \chi \geq 0, \quad (3)$$

$$w^T x + eb - y \leq e\varepsilon + \chi^*, \chi^* \geq 0,$$

144 where C is the regularization factor that reflects the trade-off between the flat-
 145 ness of regressor $f(x)$ and the maximum deviation ε which could be tolerated.
 146 The variables χ, χ^* are the slack variables introduced as a soft margin to the
 147 tolerable error ε and e is a vector of ones of appropriate dimensions ($n \times 1$).
 148 However, this is not the case always, as the feature sets might not be linearly
 149 separable. To handle such nonlinearities in the feature sets, kernel trick or often
 150 called as kernel functions are used to transform data to a higher dimensional
 151 space. After transformation via suitable mapping function $\phi : \mathbb{R}^n \rightarrow Z$, the
 152 data becomes linearly separable in the target space (high dimensional space),
 153 that is, Z . The inner product $\langle w^T, \phi(x) \rangle$ in the target space can be represented
 154 by using kernel function. Kernel functions are similarity functions which sat-
 155 isfy Mercer's theorem such that $k(x_i, x_j) = \langle \phi(x_i), \phi(x_j) \rangle$, are the elements of
 156 the kernel matrix K . Several kernel functions are available in literature like
 157 linear, polynomial with degree d , gaussian, Radial Basis Function (RBF) with
 158 bandwidth of the function σ and exponential function.

159 The SVR optimization problem can be extended into its dual form as follows:

$$\begin{aligned}
 \min \quad & \frac{1}{2} \sum_{i,j=1}^n (\alpha_i - \alpha_i^*)^T k(x_i, x_j) (\alpha_j - \alpha_j^*) + e^T \varepsilon \sum_{i=1}^n (\alpha + \alpha^*) - \sum_{i=1}^n y_i (\alpha - \alpha^*) \quad (4) \\
 \text{s.t.} \quad & e^T \sum_{i=1}^n (\alpha_i - \alpha_i^*) = 0, \quad 0 \leq \alpha, \quad \alpha^* \leq Ce,
 \end{aligned}$$

160 where α and α^* represent positive and negative Lagrange multipliers such that
 161 $\alpha_i \alpha_i^* = 0, i = 1, 2, \dots, n$. The regressor $f(x)$ can be written as

$$f(x) = \sum_{i=1}^n (\alpha_i - \alpha_i^*) k(x, x_i) + b. \quad (5)$$

162 The complexity of this regressor is independent of the dimensionality of the
 163 feature set but only depends on the number of support vectors which are nothing
 164 but the data points which separate the feature sets from each other. However
 165 the performance of the SVR also depends on the choice of kernel function and
 166 helps in reducing the computation time of the regression.

167 *2.2. Least square support vector regression*

168 Least-square support vector regression (LS-SVR) originally derived from
 169 least-square support vector classifiers (LS-SVC) proposed by [26] where equal-
 170 ity constraints are chosen and the square of the error term ε is minimized. The
 171 LS-SVR regression problem is formulated as

$$f(x) = w^T \phi(x) + b, \quad (6)$$

172 where w is the weight coefficient vector of dimension $(n \times 1)$ and $x_i \in \mathbb{R}^n$, $y \in \mathbb{R}$.
 173 The objective function to be minimized for LS-SVR is given as

$$\min \frac{1}{2} \|w\|^2 + \frac{1}{2} \gamma \sum_{i=1}^n \varepsilon_i^2 \quad (7)$$

$$\mathbf{s.t.} \quad y_i = w^T \phi(x_i) + b + \varepsilon_i, \quad (i = 1, 2, \dots, n), \quad (8)$$

174 where γ is the margin parameter and ε_i is the error term corresponding to each
 175 x_i . The optimization problem can be transformed by introducing Lagrange
 176 multipliers and is given as

$$L(w, b, \varepsilon, \alpha) = \frac{1}{2} \|w\|^2 + \frac{1}{2} \gamma \sum_{i=1}^n \varepsilon_i^2 - \sum_{i=1}^n \alpha_i (w^T \phi(x_i) + b + \varepsilon - y_i). \quad (9)$$

177 The Karush-Kuhn-Tucker (KKT) conditions for the optimization problem (9)
 178 can be obtained by partially differentiating the Lagrangian function with respect
 179 to $w, b, \varepsilon, \alpha$ which gives the solution in the matrix form

$$\begin{bmatrix} k(x, x^T) + \gamma^{-1}I & e \\ e^T & 0 \end{bmatrix} \begin{bmatrix} \alpha \\ b \end{bmatrix} = \begin{bmatrix} y \\ 0 \end{bmatrix}, \quad (10)$$

$$f_{LS-SVR}(x) = \sum_{i=1}^n \alpha_i k(x, x_i) + b, \quad (11)$$

180 where I is the identity matrix of appropriate dimension. The regressor obtained
 181 by LS-SVR is given by (11) and solves the optimization problem of smaller size
 182 than classical ε -SVR thus taking less computation time.

183 *2.3. Twin support vector regression*

184 Xinjun introduced an efficient way to solve the regression through support
 185 vector machines through a Twin Support Vector Regression (TSVR) that aims

186 to derive two non-parallel hyperplanes around the data points [27]. Similar to
 187 ε -SVR, TSVR finds two ε -insensitive functions, that is, up-bound and down-
 188 bound regressors. Further TSVR solves the convex optimization problem having
 189 size smaller than the conventional ε -SVR thus reducing significant time on CPU.
 190 The mathematical formulation of TSVR is

$$\begin{aligned} \min \quad & \frac{1}{2} \sum_{i=1}^n (y_i - e\varepsilon_1 - (x_i w_1 + e b_1))^T (y_i - e\varepsilon_1 - (x_i w_1 + e b_1)) \quad (12) \\ & + C_1 e^T \sum_{i=1}^n \xi_i, \quad \mathbf{s.t.} \quad y_i - (x_i w_1 + e b_1) \geq e\varepsilon_1 - \xi_i, \end{aligned}$$

$$\begin{aligned} \min \quad & \frac{1}{2} \sum_{i=1}^n (y_i - e\varepsilon_2 - (x_i w_2 + e b_2))^T (y_i - e\varepsilon_2 - (x_i w_2 + e b_2)) \quad (13) \\ & + C_2 e^T \sum_{i=1}^n \eta_i, \quad \mathbf{s.t.} \quad (x_i w_2 + e b_2) - y_i \geq e\varepsilon_2 - \eta_i, \end{aligned}$$

191 where $C_1, C_2 > 0$ and $\varepsilon_1, \varepsilon_2 \geq 0$ are the TSVR hyperparameters and ξ_i, η_i are
 192 the slack variables introduced as a soft margin to the error ε in optimization
 193 problem. The dual optimization problem formulation of TSVR is given by
 194 introducing a Lagrangian function [27]. Let $X = (x_1, x_2, \dots, x_n)$ denote the set
 195 of input vectors, $Y = (y_1, y_2, \dots, y_n)$ be the set of output vectors, where $y_i \in \mathbb{R}$
 196 and α, γ are the lagrangian multipliers.

197 Combining the KKT conditions [27] and optimization problem described by
 198 (12), the dual can be reformulated as

$$\begin{aligned} \max \quad & -\frac{1}{2} \alpha^T Q (Q^T Q)^{-1} Q^T \alpha + t^T Q (Q^T Q)^{-1} Q^T \alpha - t^T \alpha \quad (14) \\ & \mathbf{s.t.} \quad \alpha \in [0, C_1] \end{aligned}$$

$$\begin{aligned} \max \quad & -\frac{1}{2} \gamma^T Q (Q^T Q)^{-1} Q^T \gamma + m^T Q (Q^T Q)^{-1} Q^T \gamma - m^T \gamma \quad (15) \\ & \mathbf{s.t.} \quad \gamma \in [0, C_2], \end{aligned}$$

199 where $Q = [X \ e]$, $t = Y - e\varepsilon_1$, $m = Y + e\varepsilon_2$ and $u_2 = (Q^T Q)^{-1} Q^T (m - \gamma)$.
 200 Equations (14-15) refer to the dual of original convex optimization problem
 201 where the size of the former is smaller than classical SVR thereby making it
 202 faster than it. The final regressor for predicting raw data points is given as

$$f_{TSVR}(x) = \frac{1}{2} ((w_1 + w_2)^T x + (b_1 + b_2)). \quad (16)$$

203 *2.4. ε -Twin support vector regression*

204 Derived from Twin support vector machine discussed in previous section,
 205 Shao et al. [28] propose a novel regressor- ε -Twin support vector regression (ε -
 206 TSVR) that determines the pair of ε -insensitive functions by solving two convex
 207 optimization problems. In terms of the objective function to be minimized, ε -
 208 TSVR considers an added regularization term that solves the ill-conditioning
 209 problem of $Q^T Q$. The formulation of primal objective functions for ε -TSVR are

$$\begin{aligned} \min \quad & \frac{1}{2}C_3(w_1^T w_1 + b_1^2) + \frac{1}{2}\xi *^T \xi + C_1 e^T \xi, \\ \text{s.t.} \quad & Y - (Xw_1 + eb_1) = \xi^*, \end{aligned} \quad (17)$$

$$Y - (Xw_1 + eb_1) \geq -e\varepsilon_1 - \xi, \xi \geq 0, \quad (18)$$

$$\begin{aligned} \min \quad & \frac{1}{2}C_4(w_2^T w_2 + b_2^2) + \frac{1}{2}\xi *^T \xi + C_2 e^T \eta, \\ \text{s.t.} \quad & Y - (Xw_2 + eb_2) = \eta^*, \end{aligned} \quad (19)$$

$$Y - (Xw_2 + eb_2) \geq -e\varepsilon_2 - \eta, \eta \geq 0, \quad (20)$$

210 In the optimization problem $C_1, C_2, \varepsilon_1, \varepsilon_2$ are the hyperparameters that deter-
 211 mine the regression performance. The Lagrangian function for the above two
 212 primal problems can be written as

$$\begin{aligned} L(w_1, b_1, \xi, \alpha, \beta) &= \frac{1}{2}(Y - (Xw_1 + eb_1))^T(Y - (Xw_1 + eb_1)) \\ &+ \frac{1}{2}C_3(w_1^T w_1 + b_1^2) + C_1 e^T \xi \\ &- \alpha^T(Y - (Xw_1 + eb_1) + e\varepsilon_1 + \xi) - \beta^T \xi, \end{aligned} \quad (21)$$

213 where $\alpha = (\alpha_1, \alpha_2, \dots, \alpha_n)$ and $\beta = (\beta_1, \beta_2, \dots, \beta_n)$ are the Lagrangian multi-
 214 pliers. In order to obtain the dual of the above stated primal objective functions,
 215 KKT conditions are given by

$$\left\{ \begin{array}{l} \frac{\partial L}{\partial w_1} = 0 \Rightarrow -X^T(Y - Xw_1 - eb_2 - e\varepsilon_1) + X^T \alpha + C_3 w_1 = 0 \\ \frac{\partial L}{\partial b_1} = 0 \Rightarrow -e^T(Y - Xw_1 - e\varepsilon_1 - eb_2) + e^T \alpha + C_3 b_1 = 0 \\ \frac{\partial L}{\partial \xi} = 0 \Rightarrow C_1 e^T - \alpha - \beta = 0 \\ \frac{\partial L}{\partial \alpha} = 0 \Rightarrow Y - (Xw_1 + eb_1) \geq -e\varepsilon - \xi, \quad \xi \geq 0, \end{array} \right.$$

216

$$\alpha^T(Y - (Xw_1 + eb_1) + e\varepsilon_1 + \xi) = 0. \quad \alpha = 0, \quad \beta^T\xi = 0, \quad \beta \geq 0, \quad (22)$$

217 where $\alpha \in [0, C_1e]$ for $\beta \geq 0$. The above KKT conditions can be combined and
218 can be written as

$$-\begin{bmatrix} X^T \\ e^T \end{bmatrix} Y + \left(\begin{bmatrix} X^T \\ e^T \end{bmatrix} \begin{bmatrix} X & e \end{bmatrix} + C_3I \right) \begin{bmatrix} w_1 \\ b_1 \end{bmatrix} + \begin{bmatrix} X^T \\ e^T \end{bmatrix} \alpha = 0. \quad (23)$$

219 Let us define

$$Q = \begin{bmatrix} X & e \end{bmatrix}, \quad u_1 = \begin{bmatrix} w_1^T & b_1 \end{bmatrix}^T, \quad (24)$$

220 and rewriting (23) as

$$-Q^T Y + (Q^T Q + C_3I)u_1 + Q^T \alpha = 0. \quad (25)$$

221 Further we can write $u_1 = (Q^T Q + C_3I)^{-1}Q^T(Y - \alpha)$. The dual optimization
222 objective function for the above primal can be written as

$$\begin{aligned} \max \quad & -\frac{1}{2}\alpha^T Q(Q^T Q + C_3I)^{-1}Q^T \alpha^T + Y^T Q(Q^T Q + C_3I)^{-1}Q^T \alpha \\ & -(e^T \varepsilon_1 + Y^T)\alpha, \quad \mathbf{s.t.} \quad \alpha \in [0, C_1]. \end{aligned} \quad (26)$$

223 Similarly the other dual can be obtained as

$$\begin{aligned} \max \quad & -\frac{1}{2}\gamma^T Q(Q^T Q + C_4I)^{-1}Q^T \gamma^T + Y^T Q(Q^T Q + C_4I)^{-1}Q^T \gamma \\ & +(-e^T \varepsilon_2 + Y^T)\gamma, \quad \mathbf{s.t.} \quad \gamma \in [0, C_2]. \end{aligned} \quad (27)$$

224 The equations (26) and (27) are the duals of the primal objective optimization
225 function when the feature set X is linearly separable in n -dimensional space.
226 The end regressor $f(x)$ which is the mean of two functions $f_1(x)$ and $f_2(x)$, is

$$f(x) = \frac{1}{2}(f_1(x) + f_2(x)) = \frac{1}{2}((w_1 + w_2)^T x + (b_1 + b_2)). \quad (28)$$

227 *2.4.1. Kernel ε -Twin support vector regression*

228 However to extend this study to the non-linear regression the input set is
229 transformed into higher dimension using a suitable mapping function $\phi : \mathbb{R}^n \rightarrow$

230 \mathbb{R}^k , where k is the dimension in target space. In order to avoid the selection
 231 of appropriate mapping function, kernel functions are used to transform the
 232 data into higher dimension space. As in [28], the convex optimization problem
 233 considering kernel function $K(X, X^T)$ is given as

$$\begin{aligned} \min \quad & \frac{1}{2}C_3(w_1^T w_1 + b_1^2) + \frac{1}{2}\xi *^T \xi + C_1 e^T \xi, \\ \text{s.t.} \quad & Y - (K(X, X^T)w_1 + eb_1) = \xi^*. \end{aligned} \quad (29)$$

$$Y - (K(X, X^T)w_1 + eb_1) \geq -e\varepsilon_1 - \xi, \xi \geq 0, \quad (30)$$

$$\begin{aligned} \min \quad & \frac{1}{2}C_4(w_2^T w_2 + b_2^2) + \frac{1}{2}\xi *^T \xi + C_2 e^T \eta, \\ \text{s.t.} \quad & Y - (K(X, X^T)w_2 + eb_2) = \eta^*. \end{aligned} \quad (31)$$

$$Y - (K(X, X^T)w_2 + eb_2) \geq -e\varepsilon_2 - \eta, \eta \geq 0, \quad (32)$$

234 where C_1, C_2, C_3, C_4 are the hyperparameters for kernel-based ε -TSVR. The
 235 duals of the primal optimization problems are given as

$$\begin{aligned} \max \quad & -\frac{1}{2}\alpha^T S(S^T S + C_3 I)^{-1} S^T \alpha^T + Y^T S(S^T S + C_3 I)^{-1} S^T \alpha \\ & -(e^T \varepsilon_1 + Y^T) \alpha, \quad \text{s.t.} \quad \alpha \in [0, C_1], \end{aligned} \quad (33)$$

$$\begin{aligned} \max \quad & -\frac{1}{2}\gamma^T S(S^T S + C_4 I)^{-1} S^T \gamma^T + Y^T S(S^T S + C_4 I)^{-1} S^T \gamma \\ & +(-e^T \varepsilon_2 + Y^T) \gamma, \quad \text{s.t.} \quad \gamma \in [0, C_2], \end{aligned} \quad (34)$$

236 where $S = [K(X, X^T) \ e]$ and α, γ are the Lagrangian multipliers. The end
 237 regressor $f_{\varepsilon-TSVR}(x)$ is given as the mean of the two functions, given as

$$f_{\varepsilon-TSVR}(x) = \frac{1}{2}((w_1^T + w_2^T)K(X, X^T) + (b_1 + b_2)). \quad (35)$$

238 It should be noted that, by varying the value of C_3 in (33), the regression
 239 accuracy can be improved and is validated for one of the datasets in Section 4.

240 3. Framework of hybrid forecasting model

241 The present study deals with short-term wind speed prediction using a hy-
 242 brid method involving wavelet transform and support vector regression. Hybrid
 243 methods hold an advantage over individual methods in terms of filtering any

244 stochastic volatility. The error in wind speed prediction depends on the pre-
245 diction horizon, i.e. the time frame for which the forecasting is supposed to be
246 carried out. For market clearing operations and economic load dispatch usually
247 short-term wind speed prediction ranging from 30 minutes to 3 hours is a pre-
248 ferred choice. A hybrid method involving wavelet transform and SVR variants,
249 is used for short-term forecast for different wind sites. The wind forecasting
250 is carried out using the hybrid model, that is, Wavelet-SVR, Wavelet-LSSVR,
251 Wavelet-TSVR and Wavelet- ε -TSVR. The forecasting accuracy is evaluated by
252 computing various performance metrics like Root mean squared error (RMSE),
253 Mean absolute error (MAE), Sum of squared residuals (SSR) and Sum of squared
254 deviation of testing samples (SST), Sum of squared error of testing samples
255 (SSE) Index of agreement (IOA), Theil's U1 and U2 statistic [29]. Mathemati-
256 cally these metrics are expressed as

$$\begin{aligned}
RMSE &= \left[\frac{1}{n} \sum_{i=1}^n (\hat{x}_i - x_i)^2 \right]^{1/2}, & MAE &= \left[\frac{1}{n} \sum_{i=1}^n |\hat{x}_i - x_i| \right] \\
SSR/SST &= \frac{\sum_{i=1}^n (\hat{x}_i - \bar{x})^2}{\sum_{i=1}^n (x_i - \bar{x})^2}, & SSE/SST &= \frac{\sum_{i=1}^n (\hat{x}_i - x_i)^2}{\sum_{i=1}^n (x_i - \bar{x})^2}, \\
IOA &= 1 - \sum_{i=1}^n (\hat{x}_i - x_i)^2 / \sum_{i=1}^n (|\hat{x}_i - \bar{x}| + |x_i - \bar{x}|)^2 \\
U1 &= \sqrt{\frac{1}{n} \times \sum_{i=1}^n (\hat{x}_i - x_i)^2} / \left(\sqrt{\frac{1}{n} \times \sum_{i=1}^n x_i^2} + \sqrt{\frac{1}{n} \times \sum_{i=1}^n \hat{x}_i^2} \right) \\
U2 &= \sqrt{\frac{1}{n} \times \sum_{i=1}^n ((x_{i+1} - \hat{x}_{i+1}) / x_i)^2} / \sqrt{\frac{1}{n} \times \sum_{i=1}^n ((x_{i+1} - \hat{x}_i) / x_i)^2}
\end{aligned}$$

257 where \hat{x}_i, x_i, \bar{x} are the predicted, actual and mean values of the testing samples.

259 Figure 1 shows the block diagram of forecasting through hybrid wavelet-SVR
260 method. First, the original wind speed time series is decomposed into low fre-
261 quency and high frequency components. Further, the appropriate decomposition
262 signals are selected as inputs to the SVR forecasting model. The wavelet filter
263 chosen was daubechies 'db4' with 5-level decomposition. Wavelet transform can
264 be categorized as continuous (CWT) and discrete wavelet transform (DWT).

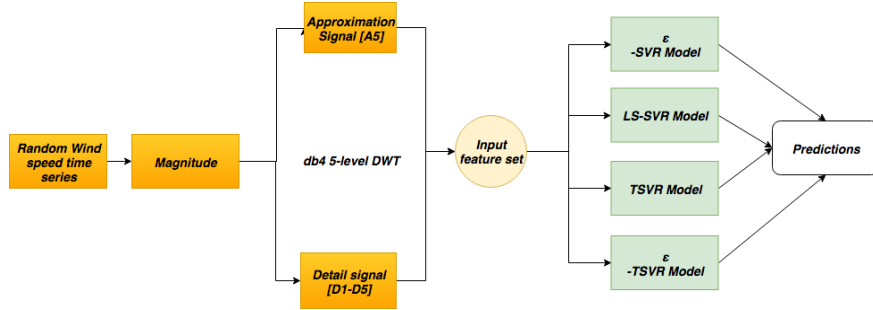


Figure 1: Wind forecasting using Wavelet transform and SVR

265 Computationally DWT is more rich than CWT due to which former finds more
 266 use in signal processing. Mathematically CWT and DWT are expressed as

$$B(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} r(x) \phi\left(\frac{x-b}{a}\right), \quad (36)$$

$$B(u, v) = 2^{-u/2} \sum_{t=0}^{N-1} r(t) \phi\left(\frac{t-v \cdot 2^u}{2^u}\right), \quad (37)$$

267 where $r(t)$ is the wind speed time series and N is its length, $\phi(\cdot)$ is the mother
 268 wavelet function, and scaling and translation parameters are functions of integers
 269 u and v . The WT process involves successive decomposition of approxima-
 270 tion signal obtained at each stage. The two signals obtained at each decomposi-
 271 tion stage are approximate and detail signals, former containing low-frequency
 272 components and later high-frequency components. The approximate (A5) and
 273 detail signals (D1, D2, D3, D4 and D5) together form a matrix of input features
 274 and wind speed is the output used in short-term wind forecasting algorithm
 275 (here SVR and its variants).

276 3.1. Description of Datasets

277 To test the hybrid wavelet-SVR wind farm sites from Spain, Western Mas-
 278 sachusetts (USA), South Dakota (USA), Victoria (Australia) and India are cho-
 279 sen with their descriptive statistics being listed in Table 1, and are selected to
 280 test the forecasting performance based on wavelet-SVR and its variants. Figure
 281 2 shows the wind speed variations for these wind farm sites.

- 282 • Paxton, MA: The wind site is located in western Massachusetts with
283 $42^{\circ}18'11.6''$ and $71^{\circ}53'50.9''$ as its coordinates. The wind speed is mea-
284 sured every 10 minutes with cup anemometers installed at a height of 78
285 m above the ground. The wind speed data ranges from January 1, 2011
286 to January 7, 2011 22:30 hrs.
- 287 • Sotavento, Spain: The wind farm is located in Sotavento, Galicia, Spain
288 with latitude $43^{\circ}21'35.9''$ and longitude $-7^{\circ}52'47.9''$. The dataset chosen
289 is for the month of October 2017 where the wind speed is measured hourly.
- 290 • Blandford, MA: Blandford is situated at 42.223° N and 72.968° E with
291 wind speed recorded at a height of 60 m above the ground with a cup
292 anemometer at every 10 minute. The wind speed data ranges from Jan-
293 uary 1, 2011 to January 7, 2011 22:30 hrs.
- 294 • Bishop & Clerks, MA: Wind monitoring site is located at 41.574° N and
295 70.249° E with anemometer installed at height of 15 m above ground.
296 The data ranges from January 1 2011 to January 7, 2011 22:30 hrs and is
297 recorded every 10 minutes.
- 298 • Beresford, South Dakota: The wind site is located at 43.088° N and
299 96.786° E and ranges from March 1, 2006 22:20 hrs to March 8, 2006
300 20:50 hrs. Wind speed is recorded every 10 minutes at a height of 20 m.
- 301 • AGL Macarthur, Victoria, Australia: Macarthur wind farm is located at
302 38.049° S and 142.190° E with 420 MW installed capacity featuring 140
303 V112-3.0 Vestas wind turbines. The hourly wind speed data is taken from
304 February 26, 2019 00:00 hrs to March 5, 2019 23:00 hrs [30].
- 305 • Muppandal, Kanyakumari, India: Located in Kanyakumari, Tamil Nadu,
306 it has a capacity of 1500 MW. Wind speed data for the month of January
307 2019 is chosen. The samples are recorded at 10 minute intervals [31].
308

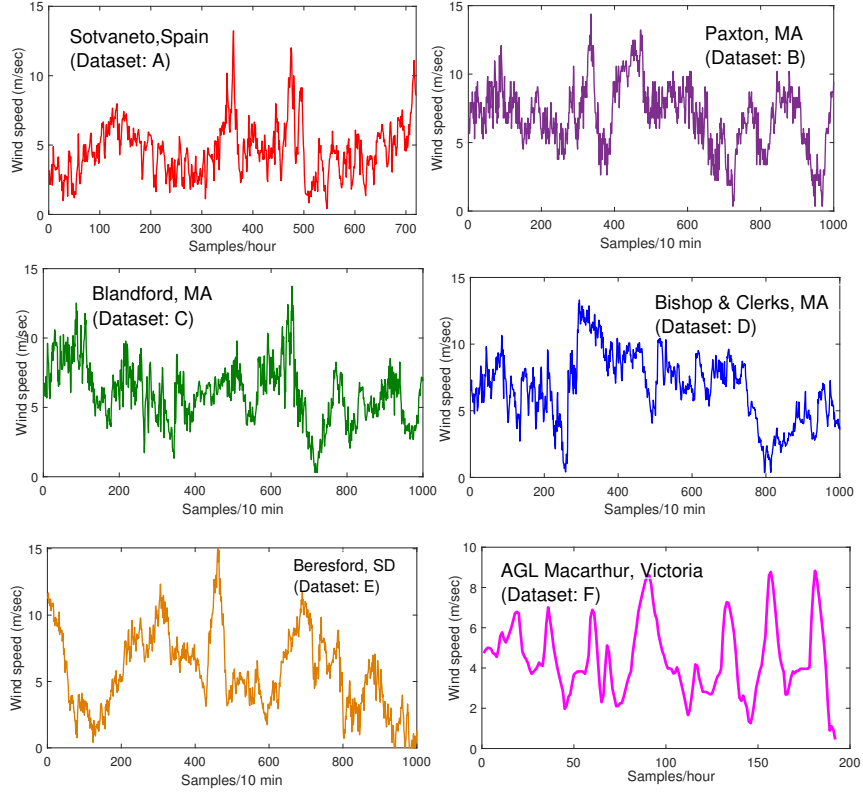


Figure 2: Wind speed for datasets A through F

Table 1: Descriptive statistics for wind speed at various wind farm sites

Wind farm (Dataset)	Max (m/sec)	Min (m/sec)	Mean (m/sec)	Std Dev
Sotavento, Spain (A)	13.23	0.41	4.6072	1.9395
Paxton, MA (B)	14.39	0.35	6.9209	2.3734
Blandford, MA (C)	13.73	0.30	6.0553	2.1242
Bishop & Clerks, MA (D)	13.31	0.36	6.7065	2.5923
Beresford, SD (E)	15.06	0.58	5.4729	2.9828
AGL Macarthur (F)	9.05	1.92	6.2926	1.5035
Muppandal, Kanyakumari (G)	8.48	0.71	4.8878	1.4641

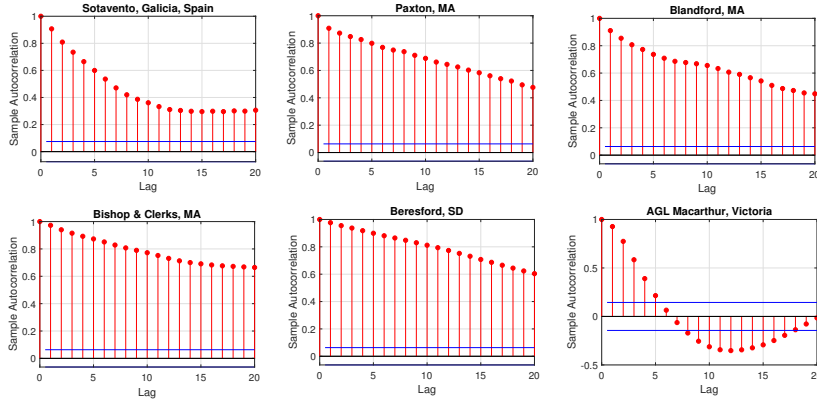


Figure 3: Periodicity of wind speed time-series for Sotavento, Paxton, Blandford, Bishop & Clerks, Beresford and AGL Macarthur

309 Figure 3 illustrates the periodicity of the wind speed time series for all
 310 datasets. The auto-correlation plots depict the correlation of time series sam-
 311 ples with itself at different lag order. For datasets A to E, we find that lag order
 312 of 1 and 2 are significantly dominant, indicating strong correlation. However,
 313 the auto-correlation for dataset F is negative for lag order 7.

314

315 3.2. Forecasting performance during Wind power ramp events

316 Wind power intermittency owing to sudden wind speed variations, is a criti-
 317 cal event in case of grid connected power plants, leading to severe consequences
 318 like low system reliability, high reserve capacity and high operational costs. A
 319 wind power ramp event is defined as rate of change in wind power generated by
 320 a wind turbine or wind farm over a short period of time exceeding a predefined
 321 threshold value (normally 50%) [32]. According to [33], power ramp event is
 322 said to occur if the change in power signal $|P(t + \Delta t) - P(t)|$ is greater than
 323 a said threshold ΔP_{ramp} . Intermittent nature wind speed leads to installation
 324 of energy storage systems in the wind farms to tackle peak demand scenarios,
 325 thus constant charging and discharging of batteries during multiple ramp events
 326 degrades their life [34]. In order to analyze the power ramp up or down events,
 327 setting the threshold power is an important task. For a given wind turbine, let

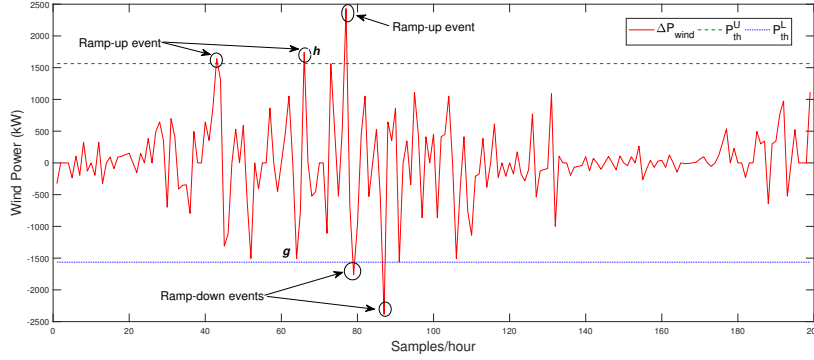
328 us say the ramp threshold power is $r\%$ of the nominal wind power. Then we
 329 can define two ramp thresholds, that is,

$$\Delta P_{ramp} = \begin{cases} +r\% \text{ of } P_{nominal} & = P_{th}^u, \\ -r\% \text{ of } P_{nominal} & = P_{th}^l, \end{cases} \quad (38)$$

330 where P_{th}^u and P_{th}^l are the upper and lower ramp thresholds respectively depict-
 331 ing ramp-up and ramp-down events in a given short period of time. We now
 332 compare different forecasting methods during power ramp events and analyze
 333 the critical conditions prevailing during such events. The forecasting methods
 334 implemented are hybrid models based on wavelet transform and ε -SVR, LS-
 335 SVR, TSVR and ε -TSVR.

336 3.3. Ramp event error analysis for ε -SVR and LS-SVR

337 Consider a power ramp-up event at points g and h as shown in Figure 4.
 338 Let the wind power at point g be P_g and at point h be P_h , and the difference
 339 $\Delta P_{gh} = P_h - P_g$ denotes change in wind power over a short time interval ΔT .



340 Figure 4: Schematic representation of wind power ramp events

341 According to ε -SVR and LS-SVR, the forecasted values are

$$\hat{P}_{g1} = (\alpha_g - \alpha_g^*)k(x, x_g) + b, \quad (39)$$

$$\hat{P}_{h1} = (\alpha_h - \alpha_h^*)k(x, x_h) + b, \quad (40)$$

$$\hat{P}_{g2} = \eta_g k(x, x_g) + b_1, \quad (41)$$

$$\hat{P}_{h2} = \eta_h k(x, x_h) + b_1, \quad (42)$$

342 at ramp points g and h such that α_g, η_g are the Lagrangian multipliers, $\hat{P}_{g1}, \hat{P}_{h1}$
343 and $\hat{P}_{g2}, \hat{P}_{h2}$ are the predicted values based on ε -SVR and LS-SVR models
344 respectively. Error in predicted value \hat{P}_{g1} and actual value P_g is given as

$$e_{SVR} = \hat{P}_{h1} - P_h - \hat{P}_{g1} - P_g, \quad (43)$$

$$e_{LS-SVR} = \hat{P}_{h2} - P_h - \hat{P}_{g2} - P_g, \quad (44)$$

345 where e_{SVR} and e_{LS-SVR} are the errors based on ε -SVR and LS-SVR models
346 respectively. If LS-SVR outperforms ε -SVR, we have $e_{LS-SVR} < e_{SVR}$, that is,

$$\hat{P}_{h1} - P_h - \hat{P}_{g1} + P_g > \hat{P}_{h2} - P_h - \hat{P}_{g2} + P_g. \quad (45)$$

347 Let us define $\beta_h = \alpha_h - \alpha_h^*$ and $\beta_g = \alpha_g - \alpha_g^*$, and by simplifying (45), we get

$$\beta_h k(x, x_h) + b - \beta_g k(x, x_g) - b > \eta_h k(x, x_h) + b_1 - \eta_g k(x, x_g) - b_1, \quad (46)$$

348 since the kernel matrix elements $k(x, x_i)$ are equal for ε -SVR and LS-SVR, the
349 equation can be further simplified as,

$$k(x, x_h) (\beta_h - \eta_h) - k(x, x_g) (\beta_g - \eta_g) > 0, \quad (47)$$

350 Thus if condition in (47) is satisfied, LS-SVR will outperform ε -SVR during
351 ramp events.

352 3.4. Ramp event error analysis for TSVR and ε -TSVR

353 Similarly TSVR and ε -TSVR can be compared based on same approach. Let
354 e_{TSVR} and $e_{\varepsilon-TSVR}$ denote the errors in the wind ramp power between points
355 g and h based on TSVR and ε -TSVR respectively and are given as

$$\hat{P}_{g3} = \frac{1}{2}(w_1 + w_2)k(x, x_g) + \frac{1}{2}(b_1 + b_2), \quad (48)$$

$$\hat{P}_{h3} = \frac{1}{2}(w_1 + w_2)k(x, x_h) + \frac{1}{2}(b_1 + b_2), \quad (49)$$

$$\hat{P}_{g4} = \frac{1}{2}(u_1 + u_2)k(x, x_g) + \frac{1}{2}(b_3 + b_4), \quad (50)$$

$$\hat{P}_{h4} = \frac{1}{2}(u_1 + u_2)k(x, x_h) + \frac{1}{2}(b_3 + b_4), \quad (51)$$

356 where $\hat{P}_{g3}, \hat{P}_{h3}$ and $\hat{P}_{g4}, \hat{P}_{h4}$ are the predicted values of wind power using TSVR
 357 and ε -TSVR respectively. The forecasted ramp power $\hat{\Delta P}_{gh}$ is then compared
 358 for two methods. The error in ΔP_{gh} for TSVR and ε -TSVR is given as

$$e_{TSVR} = \hat{P}_{h3} - P_h - \hat{P}_{g3} + P_g, \quad (52)$$

$$e_{\varepsilon-TSVR} = \hat{P}_{h4} - P_h - \hat{P}_{g4} + P_g, \quad (53)$$

359 Comparing the two ramp power errors, if, $e_{TSVR} > e_{\varepsilon-TSVR}$ we get,

$$\hat{P}_{h3} - P_h - \hat{P}_{g3} + P_g > \hat{P}_{h4} - P_h - \hat{P}_{g4} + P_g. \quad (54)$$

360 Let us define $\frac{1}{2}(w_1 + w_2) = \hat{w}$ and $\frac{1}{2}(u_1 + u_2) = \hat{u}$ and simplifying (54), we get

$$\hat{w} \left(k(x, x_h) - k(x, x_g) \right) > \hat{u} \left(k(x, x_h) - k(x, x_g) \right). \quad (55)$$

361 As long as the condition (55) is satisfied, ε -TSVR outperforms TSVR during
 362 ramp events between points g and h . The next section discusses the forecasting
 363 errors during wind power ramp events.

364 4. Results and Discussion

365 A hybrid model is built on wavelet decomposition technique and machine
 366 intelligent SVR model where 80% of data is used for training and the rest for
 367 testing. TSVR and ε -TSVR forecasting models are evaluated via-a-vis ε -SVR
 368 and LS-SVR models. For ε -TSVR, we assume the regularization factor $C_1=C_2$
 369 and $C_3=C_4$. Similarly for TSVR, we select $C_1=C_2$. The kernel function used for
 370 building the regression models is Radial basis function (RBF), with bandwidth
 371 σ , $k(x, x_i) = e^{\left(-\frac{\|x-x_i\|^2}{2\sigma^2} \right)}$. The hyperparameters C_1, C_2, C_3 and C_4 along with
 372 RBF bandwidth (σ) are chosen from a set 2^i , where $i = -9, -8, \dots, 9, 10$. Optimal
 373 parameters can be tuned manually or by grid search algorithm. Datasets related
 374 to four wind farm sites labeled A, B, C and D are chosen to test the performance
 375 of hybrid forecasting model. Dataset A consists of 720 samples out of which
 376 80% (576) are used for training process and 20% (144) are used for testing.

377 Similarly for datasets B, C and D, 800 samples are used for training and 200
378 for testing.

379 Table 2 depicts various performance indices for wavelet based hybrid SVR
380 models. For dataset A, ε -TSVR and TSVR outperformed ε -SVR by 41.95%
381 and 84.25% respectively in terms of RMSE. Similarly for dataset B, C and D, ε -
382 TSVR outperforms ε -SVR by 3.537%, 63.03% and 59.60% respectively in terms
383 of RMSE. Among all the models, ε -TSVR and TSVR outperform LS-SVR and
384 ε -SVR quantitatively in terms of RMSE and MAE for all the datasets.

385 Further, in terms of speed of computation, LS-SVR spends minimum pro-
386 cessor time owing to its smaller sized optimization problem. ε -TSVR takes less
387 time than classical ε -SVR and TSVR, and among the four datasets, datasets B,
388 C and D take more or less same computation time for the respective models.
389 The ratios SSR/SST and SSE/SST give an estimate of goodness of fit among all
390 the regression models. SSR/SST ratio value greater than 1 implies over-fitting
391 during training process which is not desirable during testing phase. Among all
392 the regressors, TSVR obtains the optimal SSR/SST and SSE/SST ratio. Fur-
393 ther, forecasting is assessed from statistical point of view by determining the
394 index of agreement (IOA), Theil's U1 and U2 statistic for all the models. From
395 Table 2, we observe that ε -TSVR and TSVR models outperform ε -SVR, LS-
396 SVR, and persistence models in terms of Theil's U1 and U2 statistic, thereby
397 indicating the forecasting accuracy of the two models is superior to the rest.

398 Figure 5 shows the forecasting results of the four variants of SVR for four
399 wind farm sites. In order to further validate the proposed hybrid forecasting
400 model, the forecast accuracy of ε -TSVR and TSVR is tested using Diebold-
401 Mariano (DM) test. The DM statistic test assumes a null hypothesis wherein
402 two forecasting models have similar accuracy [35]. We compare the DM statistic
403 of TSVR (Test 1) and ε -TSVR (Test 2) against classical ε -SVR model. The test
404 is carried out at 1% significance level for datasets A, B, C, and D and results
405 are highlighted in Table 3. Thus, by rejecting the null hypothesis from the DM
406 test, we observe that both, TSVR and ε -TSVR models have significant forecast

Table 2: Performance metrics of wavelet- ϵ -SVR, LS-SVR, TSVR and ϵ -TSVR

Dataset	Model	RMSE (m/sec)	MAE	SSR/SST	SSE/SST	IOA	U1	U2	CPU time (secs)
A	ϵ -SVR	0.1423	12.254	0.9434	0.064	1.0000	0.0233	1.1281	5.7964
	LS-SVR	0.1097	8.4668	0.9417	0.0038	1.0000	0.0028	0.9665	0.5924
	TSVR	0.0224	1.4877	0.9821	0.0008	1.0000	0.0011	0.9496	3.1864
	ϵ -TSVR	0.0823	7.6699	0.9694	0.0021	1.0000	0.00116	0.0150	2.4421
	Persistence	0.7241	71.41	1.0192	0.2925	0.9991	0.0913	1.1331	0.3024
B	ϵ -SVR	0.0424	6.8172	1.0055	0.0003	1.0000	0.0138	0.0645	11.244
	LS-SVR	0.0329	4.6550	0.9862	0.0001	1.0000	0.00340	0.0466	0.8165
	TSVR	0.0148	2.0444	0.9965	0.00003	1.0000	0.0008	0.0072	6.2343
	ϵ -TSVR	0.0409	6.8764	0.9884	0.0003	1.0000	0.0021	0.0130	3.6897
	Persistence	0.7825	66.31	1.0197	0.1437	0.9998	0.0731	1.0000	0.2560
C	ϵ -SVR	0.1791	24.211	0.9777	0.0151	0.9980	0.0453	1.3804	12.3536
	LS-SVR	0.0733	8.9438	0.9929	0.0027	1.0000	0.0021	0.0231	0.8962
	TSVR	0.0100	1.2674	0.9976	0.0004	1.0000	0.0003	0.0046	6.2235
	ϵ -TSVR	0.0662	8.7964	1.0127	0.0022	1.0000	0.0040	0.0635	3.7219
	Persistence	0.6939	54.95	1.0501	0.2934	0.9998	0.0734	1.0769	0.0818
D	ϵ -SVR	0.1901	28.8003	1.0538	0.0174	1.0000	0.0230	0.8751	11.041
	LS-SVR	0.1427	20.5274	0.9798	0.0098	1.0000	0.0129	0.6855	1.2148
	TSVR	0.0740	9.4829	0.9816	0.0026	1.0000	0.0050	0.0746	6.7960
	ϵ -TSVR	0.0768	12.1187	0.9507	0.0028	1.0000	0.0047	0.0254	9.0181
	Persistence	0.4366	34.71	1.0535	0.1156	0.9998	0.0587	0.6667	0.0925

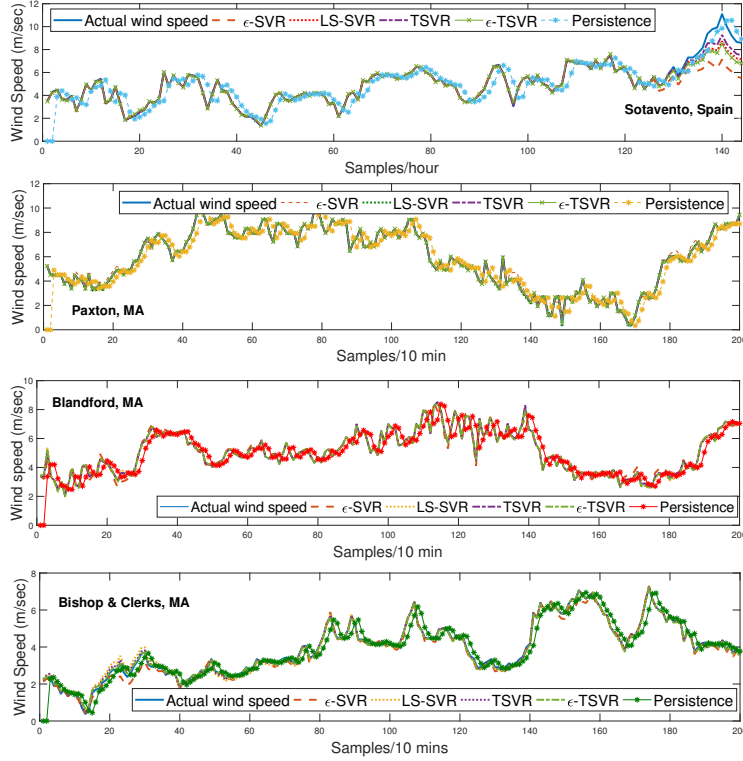


Figure 5: Forecasting results for ϵ -SVR, LSSVR, TSVR, ϵ -TSVR and Persistence model

407 superiority over ϵ -SVR model, proving the robustness of the hybrid SVR model
 408 and its variants over the persistence model.

409 In order to further validate the effect of larger dataset on our hybrid model,
 410 we select wind speed data from Blandford, MA (Dataset:C) and Muppandal,
 411 Kanyakumari (Dataset:G). The training set comprises of 4000 and 3000 samples
 412 for dataset C and G respectively and testing set consists 1000 samples. The
 413 forecasting performance is depicted in Table 4 and is illustrated in Figure 6.
 414 From Table 4, we observe that, ϵ -TSVR and TSVR perform significantly better
 415 than ϵ -SVR and LS-SVR in terms of RMSE and MAE thus indicating their
 416 superiority. Further, in terms of computation speed, ϵ -TSVR saves 93% and
 417 81% of time compared to ϵ -SVR for datasets C and G respectively.

Table 3: Diebold-Mariano test for datasets

Dataset	Diebold-Mariano Statistic	
	Test 1	Test 2
A	10.7291	9.7084
B	7.6321	7.4852
C	5.2699	5.2398
D	6.9036	6.6344

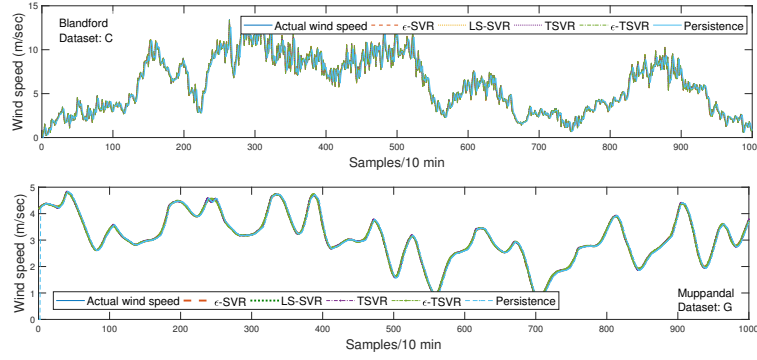


Figure 6: Forecasting results for larger datasets

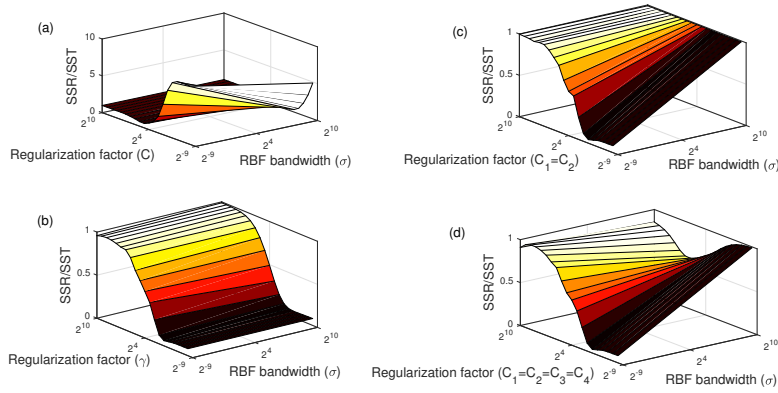


Figure 7: Variation of SSR/SST with RBF bandwidth (σ) and Regularization factor (C) for (a) ε -SVR (b) LS-SVR (c) TSVR and (d) ε -TSVR

Table 4: Performance metrics for a larger dataset

Dataset	Model	RMSE	MAE	SSR/SST	SSE/SST
C	ε -SVR	0.0416	33.7801	1.0079	0.0001
	LS-SVR	0.0194	12.7811	1.0013	0.00003
	TSVR	0.0036	2.2739	0.99994	0.00001
	ε -TSVR	0.0127	8.9721	0.9985	0.00001
	Persistence	0.8553	640.65	0.9826	0.0755
	Model	IOA	U1	U2	CPU time
	ε -SVR	1.0000	0.0031	0.1440	911.4211
	LS-SVR	1.0000	0.0014	0.0489	13.3221
	TSVR	1.0000	0.00002	0.0084	355.011
	ε -TSVR	1.0000	0.00094	0.1371	61.0762
	Persistence	1.0000	0.0633	0.7813	0.3024
Dataset	Model	RMSE	MAE	SSR/SST	SSE/SST
G	ε -SVR	0.0283	20.3760	0.9823	0.0008
	LS-SVR	0.0170	12.6992	0.9851	0.00003
	TSVR	0.0143	9.6658	0.9871	0.00002
	ε -TSVR	0.0157	10.9721	0.9910	0.00001
	Persistence	0.2053	73.4500	1.0213	0.0523
	Model	IOA	U1	U2	CPU time
	ε -SVR	1.0000	0.0041	0.6416	347.304
	LS-SVR	1.0000	0.0026	0.5163	5.9329
	TSVR	1.0000	0.0022	0.00485	70.2648
	ε -TSVR	1.0000	0.0165	0.1241	63.3087
	Persistence	1.0000	0.0318	0.6053	0.0131

418 Figure 7 shows the variation of SSR/SST ratio with RBF bandwidth (σ) and
419 regularization factor (C) for four different variants of SVR. The ratio SSR/SST
420 estimates whether the training data has been over trained or not. ε -TSVR and
421 TSVR show better variation of SSR/SST ratio for testing samples than classical
422 ε -SVR and LS-SVR with σ (keeping C constant) and C (keeping σ constant).

423 As we increase σ (from 2^{-9} to 2^{10}), the value of SSR/SST increases from 0 to 1
 424 for ε -TSVR and TSVR and remains constant for LS-SVR. However, for ε -SVR,
 425 the SSR/SST value first decreases and then increases further after $\sigma = 2^4$.

426 In our study, we choose five wind farms namely, Sotavento (Spain), Paxton
 427 (MA) and Blandford (MA), Beresford (South Dakota) [36] and AGL Macarthur
 428 wind farm, Victoria, Australia to analyze the wind power ramp events. The
 429 threshold ramp power is chosen as 15% of nominal power (P_{nom}). Wind turbines
 430 (Vestas V112) from the Danish manufacturer Vestas with rated speed 12 m/sec
 431 are selected to study the wind power ramp event. Two ramp events, that is,
 432 power ramp-up and power ramp down events are studied. The nominal wind
 433 power of the given wind turbine is 3.6496 MW. The threshold limit for ramp
 434 power events is chosen as 15% of the nominal power.

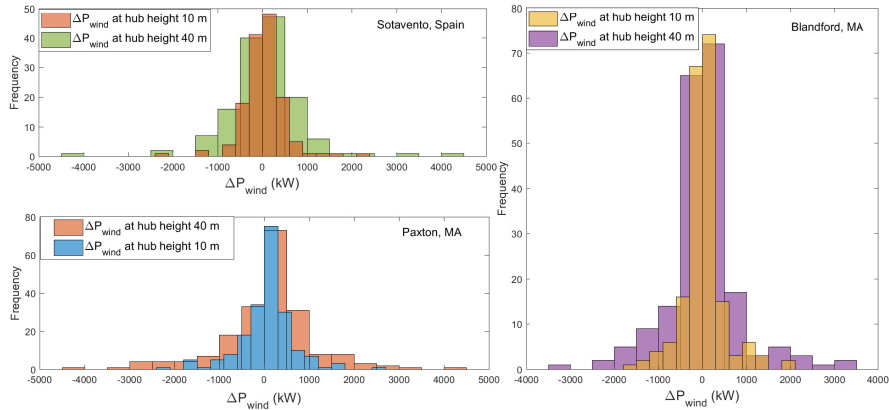


Figure 8: Frequency distribution of change in wind power with hub heights

435 Figure 8 shows the frequency distribution of change in wind power (ΔP_{wind})
 436 in successive dispatch windows for different hub heights. The wind speed data
 437 available at hub height of 10 meters is transformed at a hub height of 40 m
 438 using the wind profile power law [37] given as

$$\frac{u_h}{u_r} = \left(\frac{z_h}{z_r} \right)^\alpha, \quad (56)$$

439 where u_h , and u_r are the wind speeds (in m/sec) at desired hub height and
 440 reference hub height, z_h, z_r are the hub heights (in meters) at desired level and

reference level respectively and ($\alpha = 1/7$) is an empirically calculated constant dependent on atmospheric conditions [38].

Table 5 shows the Absolute error (AE) values computed for wind power ramp-up and ramp-down events for different wind farm sites. During ramp-up events for all the wind sites, ε -TSVR performs better than TSVR, LS-SVR and classical ε -SVR.

Table 5: Performance metric (AE) during wind power ramp events

Wind Farm	Model	Wind power ramp event	
		Ramp-up	Ramp-down
Sotavento, Spain	ε -SVR	0.7245	0.7626
	LS-SVR	0.4587	0.5303
	TSVR	0.3600	0.4191
	ε -TSVR	0.1414	0.2019
Paxton, MA	ε -SVR	0.0454	0.0174
	LS-SVR	0.0347	0.0133
	TSVR	0.0118	0.0055
	ε -TSVR	0.0018	0.0104
Blandford, MA	ε -SVR	0.0574	0.8058
	LS-SVR	0.0350	0.1650
	TSVR	0.0237	0.1454
	ε -TSVR	0.0161	0.1211
Beresford, South Dakota	ε -SVR	0.0657	0.1074
	LS-SVR	0.0500	0.1058
	TSVR	0.0074	0.0025
	ε -TSVR	0.0067	0.0021
AGL Macarthur, Victoria, Australia	ε -SVR	0.2540	0.5497
	LS-SVR	0.1221	0.3624
	TSVR	0.0669	0.1877
	ε -TSVR	0.0570	0.2821

447 From Figure 8, we see that the probability of wind power ramp event in-
 448 creases if wind speed is recorded at a hub height above the ground. The number
 449 of wind power ramp events for five wind farm sites are illustrated in Figure 9.

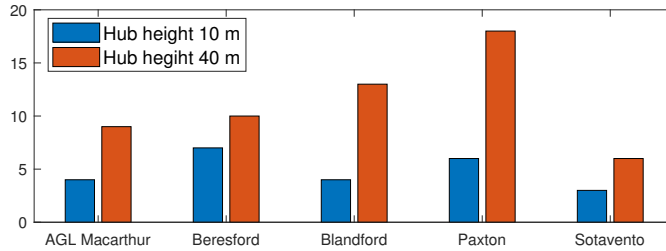


Figure 9: Frequency of number of wind power ramp events with different hub heights

450 5. Conclusion

451 In this paper, we study hybrid machine intelligent SVR models for short-
 452 term wind forecasting built on wavelet transform decomposition technique. A
 453 fourth order daubechies (db4) wavelet filter is chosen to carry out the wind speed
 454 time-series decomposition for four different wind farm sites. Among these regres-
 455 sors, the hybrid model based on TSVR and ε -TSVR proves a better short-term
 456 forecast choice based on the performance indices for the four datasets. Compu-
 457 tationally, LS-SVR takes the minimum time on CPU, and ε -TSVR takes less
 458 computation time than ε -SVR owing to its smaller sized optimization problem.
 459 The wind speed forecasting accuracy for all the hybrid models can be further im-
 460 proved by optimally selecting the SVR hyperparameters: RBF bandwidth and
 461 regularization constants. Further, the wind power ramp events are studied and
 462 under certain conditions ε -SVR and LS-SVR, and TSVR and ε -TSVR forecast
 463 errors were compared. Among the regressors, ε -TSVR outperformed TSVR, LS-
 464 SVR and ε -SVR in terms of absolute error. The ramp events are analyzed for
 465 different hub heights and the number of recorded ramp events increased signifi-
 466 cantly with height. Thus, this machine intelligent hybrid methodology improves
 467 the forecasting performance of wind farms with uncertain wind conditions like
 468 ramp events.

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