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Mitigating Nonlinear Harmonics in Diesel Electrical Ship Network by Model Predictive Control

Ravindra Sharma[1], Dr. Chandrakant Sharma[2]

[1]Senior Lecturer, Ujjain Polytechnic College, Ujjain, Madhya Pradesh, India
Corresponding Author's Email: *ravindra010775[at]gmail.com*

[2]Associate Professor, Department of Electrical Engineering, Ujjain Engineering College, Ujjain, Madhya Pradesh, India
Email: *parth.ckd[at]gmail.com*

Abstract: ***The challenge of mitigating harmonics in diesel electrical ship networks is due to the presence of non-linear loads. The main source of harmonics in the power network is the rectification circuits of the Variable Frequency Drives (VFDs) used for propelling the engines. There are various VFDs in use today based on the power level, pulse rate, and the architecture of the system, as well as the type of rectifier diodes, each of which produces different levels of harmonic currents. International and national standards require limiting Total Harmonic Distortion (THD) at the points of common coupling at the bus level in ship networks. Dynamic filtering is an effective solution for harmonic mitigation that can enhance the performance of the system. However, active filtering methods that aim to supply the smaller local harmonic components to non-linear loads to ensure the output contains only the fundamental component are not enough to mitigate harmonic pollution in the rest of the power system. As a result, local load compensation has become the main tool for active harmonic filtering. With all the activities contributing to the compensation concept, there is room for further optimization. Active filters, with their fast harmonic current dynamic performance, can benefit from performance optimization methods to adjust the current sampling rate in response to changing spectral circumstances. The system-level optimization technique will create a harmonic current reference that will induce the ideal current harmonic distribution needed to reduce THD on all the system buses.***

Keywords: harmonic mitigation, diesel electrical ship networks, Variable Frequency Drives, Total Harmonic Distortion, active filtering

1. Introduction

Harmonics refer to any deviation from a pure sinusoidal voltage or current waveform, which is usually produced by an ideal voltage source and linear loads. In a diesel-electric ship, the main source of harmonics in the power network is the rectification circuits of the Variable Frequency Drives (VFDs), which are used to control the propulsion engines. Today, there are various types of VFDs in use, each with different levels of harmonic currents, and based on factors such as power level, pulse rate, and system architecture [1]-[4]. To reduce harmonic distortion in a power system, inductive and capacitive passive filtering systems can be installed. These systems can effectively reduce the impact of harmonic loads on the overall system, especially for substantial non-linear loads. Tunable harmonics filters for dominant harmonics and specified harmonics spectrums are also used. High-pass filters may also be used to mitigate a broader spectrum of higher-order harmonics [5], [6]. However, care should be taken in designing passive filters to prevent resonances that amplify other harmonic content, especially if the installation is subject to frequent changes [7]. Another option for reducing harmonics is the use of series-connected broadband active harmonic mitigation filters. The optimization algorithm is designed to accomplish this while using the minimum amount of active filter power. This study explores non-linear programming techniques to evaluate optimization methods that use the filter capacity to generate ideal harmonic current waveforms in real-time. The technique employs the amplitude and phase of all harmonic components to reduce the total system THD while minimizing filtering power. The optimization model is defined by a non-linear model predictive control (NMPC) and both time-varying and continuous controllers [10]. The primary objective of this study is to produce an optimized filtering reference current that will improve the electric grid THD conditioning compared to local filtering techniques while still meeting the specifications for electrical ships. The study compares linear and nonlinear optimization methods and analyzes multiple shooting and collocation approaches for nonlinear model predictive control (NMPC).

2. Model of the Power Distribution Grid

The power distribution grid maritime ship developed to withstand power failures brought about by shorted distribution systems, faults induced by various loads, and tripped generators. Modern electric grid systems that include protective relays, including bus-tie breakers, frequently accomplish these. Figure 1 is a simple example of a container AC distribution network with generation units, two loads, and an active harmonic filter; it ignores the resilience of redundancy buses and public transportation breakers. For the reliable design of shipboard power systems, see [11].

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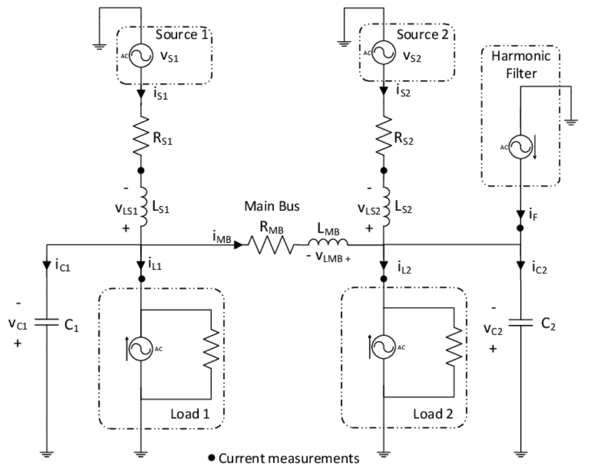

Figure 1: Grid for distributing AC power simplified

Table 1: Grid parameters used for power distribution

Value	Parameter
1mH	LMB
1mH	LS1
1mH	LS2
(.1. LMB .ώ) Ω	RMB
(.1. LS2 .ώ) Ω	RS2
(.1. LS1 .ώ) Ω	RS1
C1	0.1 µF
C2	0.1 µF

a) Model formulation

Kirchhoff's voltage and current rules to develop the mathematical model for the electricity distribution grid shown in Figure 1, written as

$$LS1.\frac{di_{S1}}{dt}=US1- RS1.iS1-UC1$$
$$C1.\frac{dU_{C1}}{dt}=iS1- iMB-iL1 \quad (1)$$
$$LMB.\frac{di_{MB}}{dt}=US1- RMB.iMB-UC2$$
$$C2.\frac{dU_{C2}}{dt}=iMB- iS2-iL2+iF$$
$$LS2.\frac{di_{S2}}{dt}=US2- RS2.iS2-UC2$$

It must capacitors are part of the power grid model for model estimation and values low to have an equation primarily determined with confidence with a voltage phase shift of ØV. The generators treat as optimal voltage sources.

$$V(t)=\sqrt{2}VrmsSin(wt+ØV) \quad (2)$$

While the non-linear demands represented by the current with harmonic content of order 13,11,7,5 and 3 as well as phasing shifts ØL,i and peak values (amplitudes) IL,i,

$$iL(t)=\sum_{i} IL,i\ Sin(iwt+Ø\ IL,i) \quad \forall i€\{1.7k+1\}\ k=1,2\} \quad (3)$$

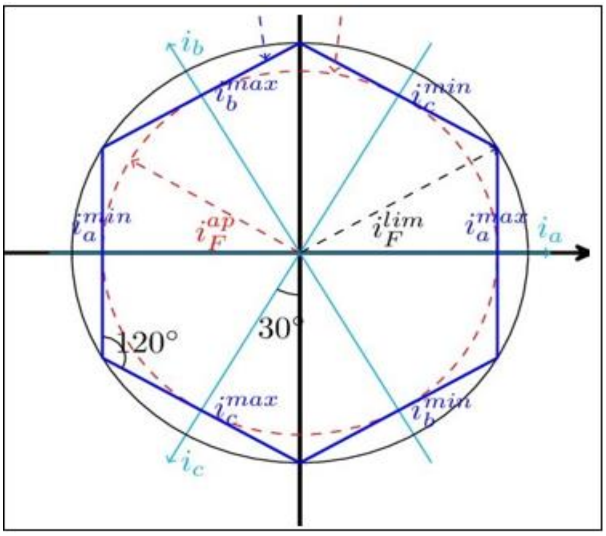

Figure 2: Harmonic filter constraints

To reduce harmonic propagation inside the container distribution network, higher cognitive harmonic components supplied by the harmonic filter, which is modeled as a current. The filter model is formally defined as

$$If(t)=\sum_{i} IF,i\ Sin(iwt+Ø\ IF,i) \quad \forall i€\{7k+1\}\ k=1,2\} \quad (4)$$

Where IF,i is the current harmonic pipe's peak value (signal). Due to power demand and consumption imbalances, the fundamental frequency may deviate from the rated value. For the goal of simulating such harmonic excursions, disruptions

$$f(t)=ff+Atsin(2\pi ftt) \quad (5)$$

Where f(t) is the rate of the frequency range, At is the peak of the frequency, and ff is the resonance frequency. The frequencies deviations rate, ft, is typically between 0.1 and 1.Hz, with the estimated frequency peak, At, being between 1 and 5 Hz. Thus, w:= w(t) = 2µf(t) gives the time-varying frequency response (t).

3. Optimization Methods

To reduce the average harmonic distortions at all buses of the container dispersion is the optimization's overarching goal by producing a perfect current harmonic reference voltage for the active filter inside the device. The non-linear model predictive (NMPC) control method is one way to improve filter currents. The NMPC method uses baseline measures as initialization for the optimization problem and re-optimizes the control after every complete optimization period. It built simpler plant models. In this paper's discussion of the NMPC problem, the filter's present magnitude and phase are both treated as (i) constant controls and (ii) time-changing controls during one optimization horizon. Collocation and simultaneous shooting are two NLP techniques to tackle the issue.

The problem is present in the standard format before considering multiple and collocation firing techniques. The goal of the task will be to limit overall harmonic currents in the distribution network through control and stop harmonic components from spreading across the network that distributes power. Considering that the thirteenth, eleventh, seventh, and fifth higher cognitive harmonics produced by a six-pulse rectifier are understood and given by

$$i_L^{lin}=\left\{V(t) = i_{L,\alpha,i}\ Sin\ i(wt + \emptyset L, i)\ V(t) = i_{L,\beta}\ , i\ Sin\ i(wt + \emptyset L, i + \tfrac{\pi}{2})\ \right\} \quad (11)$$

A$\forall i \in \{6k \pm 1, where\ k = 1,2\}$And the state vector of algebra is represented by

$$Z=\left[v_{s1}^T, v_{s2}^T, i_{L2}^T, i_F^T, (i_{L1}^{hh})T, (i_{L2)T}^{h}e,\right]T \quad (12)$$

where the filter current iF is the three-phase three-wire extensions of equation (3) given in the frames, the harmonic components of each load, i_{L1}^{hh}, and $i_{L2)T}^{hh}$, are given by the equation (3), and the loads, iL1 and iL2, are the three-phase three-wire version of equation (4) given inside the frame (11). Provided by is the dynamic state vector.

$$x=[i_{S1}^T, i_{S2}^T, i_{MB}^T, v_{C1}^T, v_{c2}^T]T \quad (13)$$

a) Controls for changing and constant time in problem formulation:

The control can be considered parameters if continuous controls to exist across the optimization horizon. Consequently, the parameter vector is provided by

$$P=[I_F, \alpha, i, I_F, \beta, I, \emptyset_F, i]T \quad (14)$$

A$\forall i \in \{6k \pm 1, where\ k = 1,2\}$

and that U = 0 determines the control vector. We define the variables as controllers if time-varying characteristics are to be employed to solve the issue, and the control vector is given by

$$U= P=[I_F, \alpha, i, I_F, \beta, I, \emptyset_F, i]T \quad , \quad \forall i \in \{6k \pm 1, where\ k = 1,2\} \quad (15)$$

and p = 0 determines the parameter vector. The current formulation of the NMPC issue is

$$AV(x, z, u, p) = \sum_{n=1}^{N} l(x_n, z_n, u_{n-1,p})$$
$$xn=f(x_n, z_n, u_{n-1,p}),\ \forall n \in \{1,2,3,,4,5, \ldots\ldots\ldots . N\}$$
$$h(x_n, z_n, u_{n-1,p})=0,\ \forall n \in \{1,2,3,,4,5, \ldots\ldots\ldots . N\}$$
$$g(x_n, z_n, u_{n-1,p})\leq 0|\ i_{F,n} \in S,\ \forall n \in \{1,2,3,,4,5, \ldots\ldots\ldots . N\} \quad (16)$$

Initial values x0, z0, iF,0∈ S is given.

Where index n is a control point, equality and unequal treatment by h() and g(), correspondingly, and index n is a control point. With consistent weights q1, q2, the phase cost function l() for static control minimizing the harmonic distortions close to the loads is

$$l(x, z, u, p)=q1(i_{F,\alpha}-i_{L1,\alpha}^{hh})2+q1(i_F, \beta-(i_{L1,\beta)}^{hh})2+q2(i_{F,\alpha}-i_{L2,\alpha}^{hh})2+q2(i_F, \beta-(i_{L2,\beta)}^{hh})2 \quad (17)$$

Controls give the stage cost function with temporal variations.

$$l(x, z, u, p)=q1(i_{F,\alpha}-i_{L1,\alpha}^{hh})2+q1(i_F, \beta-(i_{L1,\beta)}^{hh})2+q2(i_{F,\alpha}-i_{L2,\alpha}^{hh})2+q2(i_F, \beta-(i_{L2,\beta)}^{hh})2+qu(i_{lf\,i_F,\beta}^{T})2 \quad (18)$$

uIF ∈u, where q1, q2, and qu are constant weights and contain the amplitudes of the filter. The final component of equation (18) to reduce the filtering amplitude and frequency and, as a result, the filter's power rating. Also, it adds reliability and stability against model uncertainties. Because reducing harmonic distortions in the electrical system is more crucial than lowering the power rating, qu ∈q1, q2.

b) Direct Collocation:

In a direct collocation technique, polynomials estimate the condition trajectories that satisfy the ODE (16) on each control interval inside the optimization horizon. Approximation points, which have the same dimension as the space vector formulation and serve as additional decision variables in the NLP scheme, parameterize each polynomial. The Gauss-Radau collocation points of degree. When t0 indicates the beginning of a control interval, n∈N represents the number of control intervals, and d is 5, we have this for every management interval.

T = [0, 0.051104, 0.376843, 0.563590, 0.900240, 1]
t1nj := t1n0 + Δτj , ∀j = 0, . . . , s + 1., Where s is distance.

We define a Lagrangian polynomial basis by using xj to represent the dynamic state vector at time point t.

$$Di(T)=\prod_{S=0,S\neq i}^{D} \frac{T-T_r}{T_i-T_r} \quad (19)$$

Such that

$Di(Tr)=\{1, if\ i = s\ 0, otherwise$

and roughly represent the state trajectory as

$$x(tni)=\sum_{i=0}^{D} D_r(\frac{t_{ni-t_{no}}}{\Delta T_i})xr \quad (20)$$

For the control intervals n = 1,..., N, in particular, we have

$$x(tni)=\frac{1}{\Delta T_i}\sum_{r=0}^{D} D_r(T_r) \quad (21)$$
$$xn,d+1=\sum_{i=0}^{D} D_r(1)x_{nr} \quad (22)$$

It provides the equations for collocation

$$\Delta Tif(x_n, z_n, u_{n-1,p})=0, i=0,1,2,\ldots\ldots\ldots\ldots, D \quad (23)$$
$$Xn,d+1-\sum_{i=0}^{D} D_r(1)x_{nr} = 0,\ n=1,2,3,\ldots\ldots\ldots, N-1. \quad (24)$$

Which each control period must satisfy. The NLP formulation described in eq. (23) is supplemented with the collocation and continuity equations, eq. (16). The collocation technique's accuracy typically increases by using multiple intermediate collocation locations for each control period [13]. The collocation approach has proven to be beneficial in sophisticated NLP formulations, even though the derivative of the differential equations is proximate by polynomials, an increase in the number of choice variables, and an equality constraint. For further information on the collocation method, see [13].

c) Direct Multiple Shooting:

The DAE (Differential Algebraic Equation) models independently integrated in each interval in the multiple-firing approach, which divides the time domain into smaller time periods [13]. The controls in direct multiple shooting discretized on the coarse grid that each interval provides. The NLP gave equality restrictions to maintain the states' consistency throughout intervals. The equality constraints that hold the intervals n N together are granted by the dynamic state vector x at the beginning of interval n as xn(tn,0) and the end of the interval as xn(tn,1).

$$xn-1(tn-1,1) - xn(tn,0) = 0, n = 2, . . . , N, \quad (25)$$

where x1(0) = x0, the starting point. The NLP formulation described in eq. (24) and the equality restrictions are combined here (16). Explicit Runge-Kutta 4 (RK4) is the integration approach employed in this paper to implement the multiple shooting method [13, ch. 9].

As can be observed, the collocation approach is generated based on an implicit includes integration. It does not necessitate stand-alone integrators due to the trajectory assumptions, in contrast to the simultaneous shooting technique, which requires an explicit integration scheme.

d) Implementation Aspects

The CasAdi framework, a symbolic framework for algorithm differentiation and numeric optimization, is used to construct Python's collocation and multiple-shot techniques [14]. The IPOPT NLP algorithm is employed. It should Python serves as a proof-of-concept and doesn't offer a real-time framework appropriate for this issue.

4. Results

The results of the optimization process, using both constant control and time-varying constraints, are displayed in Figure 3 for both multiple shooting and collocation methods. When operating near the physical limits of the pipe, represented by I lim f, time-varying controls prove to be more effective than constant controls in reducing the total harmonic distortion (THD), allowing for additional filtering while still staying within the physical constraints of the filter. The solutions using time-varying parameters converge when the filter limit is increased, indicating that the answers are well within the filter's boundaries. The use of time-varying controls in optimization leads to fewer THDs when a small filter is used in high harmonic pollution environments, as it takes advantage of the filter phases. Multiple shooting produces lower THD values compared to collocation, which is due to the collocation method's approximate representation of dynamic states. Increasing the number of discretization steps in collocation will not lead to convergence, but will instead increase computing expenses. It is important to have clear and precise notation when creating an optimization technique for loads with high harmonic frequencies, so the frequency of partitioning must be at least two times greater than the power flows, following the Nyquist-Shannon theorem, The maximum harmonic frequencies in this situation by max = {13. (50 ±2 Hz)} = 676 Hz. The collocation's finite difference frequency is $\frac{35}{0.025s}$, = 1400 Hz. It is crucial that the quantity of finite difference steps not go above the active filter's capacity if the filter is to utilize the entire optimization horizon's solution.

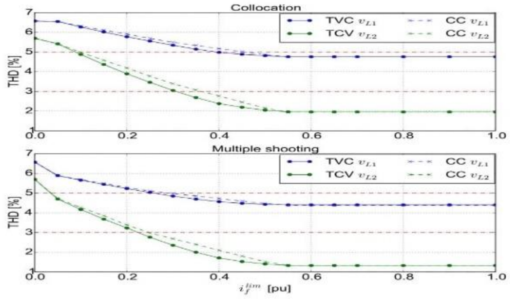

Figure 3: THD values employing collocation and multiple shooting using Time-Varying Controls (TVC) and Constant Controls for various filter current limitations (CC).

A comparison of different methods that use both time-varying and constant controls is displayed in Figure 4. A local filtering method aimed at removing only harmonic pollution from load 2 is included as a reference. The results indicate that the optimization approach produces better results than the local filtering method. This comparison includes multiple shooting and collocation techniques with both time-varying and constant controls. Since load 1 contains more harmonic pollution than load 2, the local filtering approach only considers load 2, which may not be the best option. The optimization technique allows for the consideration of multiple sources and asymmetric loads simultaneously, which can lead to the identification of the optimal filter current and lowest overall THD.

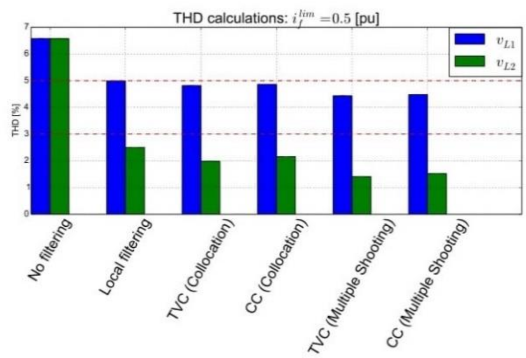

Figure 4: With Time-Varying Controls (TVC) and Constant Controls, multiple shooting and collocation are compared (CC).

The computational complexity of the optimization scheme is an important factor to consider during implementation. Figure 5 displays the average shooting time (with warm start) for different filter current limits, i_f^{lim}, when colocation and multi-shooting are both used. Optimization was carried out on a laptop with an Intel Core i7-4600U CPU running at 2.10GHz x 4.

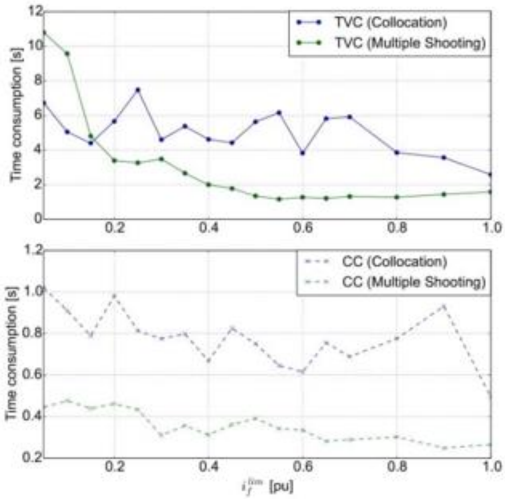

Figure 5: Average time spent using collocation, multiple shots, Time-Varying Controls (TVC), and Constant Controls for various filter current limitations (CC).

When the filter width is not overly restrictive, the convergence of multiple shooting is faster than collocation for time-varying controls. It has also been observed that as the filter's current limit increases, the time consumption of multiple shooting becomes more consistent compared to collocation. Although the time differences between the two methods are significant when dealing with time-varying controls, they are relatively low when constant controls are used. This is because the linear problem formulation results in reduced time consumption for both collocation and multiple shooting when constant controls are used. It has been observed that collocation takes much longer to complete than multiple shooting with constant settings. To try to obtain a better solution, increasing the number of finite difference steps for collocation may cause additional computational costs. The number of iterations required to solve the optimization problem using both collocation and multiple shooting, with both time-varying and constant controls, is shown in Figure 6. When the filter is not too narrow, multiple shooting requires fewer iterations to converge to a solution compared to collocation for time-varying controls. In terms of the number of iterations, multiple shooting is also more stable than collocation. When compared to collocation, multiple shooting requires fewer iterations for constant control and therefore provides a solution more quickly, with lower THD values. On the other hand, collocation is slower and provides solutions with higher THD values.

5. Conclusion

The article discusses the use of two harmonic filter controllers that employ non-linear programming with collocation and multiple firing. Both time-varying and constant controls were utilized. The active filter control problem is a challenge in Nonlinear Model Predictive Control (NMPC). The use of time-varying controls provided better filtering results when the filter was operating close to its physical limits, but had higher computational costs compared to constant controls. The multiple shooting approach generated better Total Harmonic Distortion (THD) values with fewer computational steps than the collocation method. Two sets of restrictions were proposed: linear hexagonal constraints and non-linear circular constraints. The hexagonal conditions provided linear approximations from the phase constraints, while the circular constraints reflected the actual physical limits of the filter based on the bounds of the filter's current vector. The research found that the hexagonal constraints were appropriate for NMPC with constant controls and had lower computational costs than NMPC with time-varying controls. However, the NMPC with time-varying controls revealed that the linear hexagonal constraint violated the physical limits when the filter was operating close to them. Removing the filter phases from the optimization problem and applying the hexagonal constraints showed that the problem was linear, as the filter phases were not used in the constant control scenario. In the future, the authors plan to focus on implementing the solution in a real-time setting, resolving the optimization as a linear problem with constant controls and linear hexagonal constraints using a suitable solver.

References

[1] P. Crapse, J. Wang, J. Abrams, Y.-J. Shin, and R. Dougal,"Power quality assessment and management in an electric ship power system," in IEEE Electric Ship Technologies Symposium, 2007. ESTS '07., May 2007, pp. 328–334.

[2] S. Bourguet, P. Guerin, and R. LeDoeuff, "Noncharacteristic harmonics generated by frequency converter," GE44 , Laboratory, Saint-Nazaire, France, All Electric Ship 2003, Edinbugh., 2003.

[3] H. Akagi, Y. Kanazawa, and A. Nabae, "Instantaneous reactive power compensators comprising switching devices without energy storage components," IEEE Transactions on Industry Applications, vol. IA-20, no. 3, pp. 625–630,May 1984.

[4] H. Akagi, E. Watanabe, and M. Aredes, Instantaneous Power Theory and Applications to Power Conditioning, ser. IEEE Press Series on Power Engineering. Wiley, 2007.

[5] E. Tedeschi, "Cooperative control of distributed compensation systems in electric networks under non-sinusoidal operations," PhD thesis, University of Padova, Department of Electrical Power Engineering, 2009.

[6] I. Evans and A. Hoevenaars, "Meeting harmonic limits on marine vessels," in IEEE Electric Ship Technologies Symposium, 2007. ESTS '07, May 2007, pp. 115–121.

[7] T. Hoevenaars, I. Evans, and A. Lawson, "New marine harmonic standards," vol. 16, no. 1, January 2010, pp.16–25.

[8] A. Garces, M. Molimas, and P. Rodriguez, "A generalized compensation theory for active filters based on mathematical optimization in ABC frame," Electric Power Systems Research, Elsevier Journal, vol. 90, no. 0, pp. 1 – 10, 2012.

[9] P. C. See, V. C. Tai, M. Molimas, K. Uhlen, and O. B. Fosso, "Enhanced active power filter control for nonlimear non-stationary reactive power compensation," arXiv:1206.4232, Cornell University Library, Jun 2012.

[10] DNV-OS-D201, “Electrical installations, offshore standards,” Jan. 2005.

[11] M. Patel, Shipboard Electrical Power Systems, ser. Shipboard Electrical Power Systems. Taylor & Francis, 2011.

[12] J. A. Suul, “Control of Grid Integrated Voltage Source Converters under Unbalanced Conditions,” PhD thesis, Norwegian University of Science and Technology, Department of Electrical Power Engineering, March 2012.

[13] L. Biegler, Nonlimear Programming: Concepts, Algorithms, and Applications to Chemical Processes, ser. MOS-SIAM Series on Optimization. Society for Industrial and Applied Mathematics (SIAM, 3600 Market Street, Floor 6, Philadelphia, PA 19104), 2010.

[14] J. Andersson, “A General-Purpose Software Framework for Dynamic Optimization,” PhD thesis, Arenberg Doctoral School, KU Leuven, Department of Electrical Engineering (ESAT/SCD) and Optimization in Engineering Center, Kasteelpark Arenberg 10, 3001-Heverlee, Belgium, October 2013.

[15] H. Ferreau, C. Kirches, A. Potschka, H. Bock, and M. Diehl, “qpOASES: A parametric active-set algorithm for quadratic programming,” Mathematical Programming Computation, vol. 6, no. 4, pp. 327–363, 2014.

[16] J. Mattingley and S. Boyd, “Cvxgen: a code generator for embedded convex optimization,” Optimization and Engineering, vol. 13, no. 1, pp. 1–27, 2012.

[17] A. Domahidi, A. Zgraggen, M. Zeilimger, M. Morari, and C. Jones, “Efficient interior point methods for multistage problems arising in receding horizon control,” in IEEE Conference on Decision and Control (CDC), Maui, HI, USA, Dec. 2012, pp. 668 – 674.

[18] G. Frison, D. Kwame Minde Kufoalor, L. Imsland, and J. Jørgensen, “Efficient implementation of solvers for limear model predictive control on embedded devices,” in Proceedings of 2014 IEEE International Conference on Control Applications (CCA), 2014, pp. 1954–1959.

[19] D. M. Kufoalor, S. Richter, L. Imsland, T. Johansen, M. Morari, and G. Eikrem, “Embedded Model Predictive Control on a PLC Using a Primal-Dual First-Order Method for a Subsea Separation Process,” in Mediterranean Conference on Control and Automation, Palermo, Jun. 2014.

[20] P. Lezana, R. Aguilera, and D. Quevedo, “Model predictive control of an asymmetric flying capacitor converter,” IEEE Transactions on Industrial Electronics, vol. 56, no. 6, pp. 1839–1846, June 2009.

[21] T. Geyer, G. Papafotiou, and M. Morari, “Model predictive control in power electronics: A hybrid systems approach,” in 44th IEEE Conference on Decision and Control 2005, and 2005 European Control Conference. CDC-ECC ’05., Dec 2005, pp. 5606–5611.

[22] B. Houska, H. Ferreau, and M. Diehl, “An AutoGenerated Real-Time Iteration Algorithm for Nonlimear MPC in the Microsecond Range,” Automatica, vol. 47, no. 10, pp. 2279–2285, 2011.

[23] J. Jerez, P. Goulart, S. Richter, G. Constantinides, E. Kerrigan, and M. Morari, “Embedded predictive control on an FPGA using the fast gradient method.” IEEE, 2013, pp. 3614–3620.

[24] F. Xu, H. Chen, W. Jin, and Y. Xu, "FPGA implementation of nonlinear model predictive control," in The 26th Chinese Control and Decision Conference (2014 CCDC), May 2014, pp. 108–113