Final Report

Title Page

PROJECT TITLE: Low Head, Vortex Induced Vibrations River Energy Converter

AWARD NUMBER: DE-FG36-05GO15162

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RECIPIENT: Vortex Hydro Energy LLC

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WORKING PARTNERS: University of Michigan College of Engineering, University of Michigan Marine Hydrodynamics Laboratory

COST-SHARING PARTNERS: University of Michigan College of Engineering ($3,000 cash), University of Michigan Hydrodynamics Laboratory ($5,000 in-kind)

PROJECT TEAM: DOE HQ Program Manager - Lisa Barnett
DOE Field Project Officer - Deborah Weems

DISTRIBUTION RESTRICTIONS: None

Executive Summary

Vortex Induced Vibrations Aquatic Clean Energy (VIVACE) is a novel, demonstrated approach to extracting energy from water currents. This invention is based on a phenomenon called Vortex Induced Vibrations (VIV), which was first observed by Leonardo da Vinci in 1504AD. He called it 'Aeolian Tones.' For decades, engineers have attempted to prevent this type of vibration from damaging structures, such as offshore platforms, nuclear fuel rods, cables, buildings, and bridges. The underlying concept of the VIVACE Converter is the following: Strengthen rather than spoil vortex shedding; enhance rather than suppress VIV; harness rather than mitigate VIV energy. By maximizing and utilizing this unique phenomenon, VIVACE takes this "problem" and successfully transforms it into a valuable resource for mankind.

The VIVACE Converter satisfies typical DOE and California Energy Commission requirements:

(1) Have high energy density
(2) Be unobtrusive to navigation
(3) Be unobtrusive to coastal property
(4) Be unobtrusive to marine life
(5) Have good robustness
(6) Have low maintenance
(7) Achieve certain life cycle cost target
(8) Have a design life of at least 10 years

VIVACE has numerous advantages, which improve installation survivability in the hostile underwater environment and enable low-cost power production by decreasing capital cost and minimizing maintenance.

- High energy density – enables low cost energy to be produced from relatively small installations.
- Simple and rugged moving parts – allows for robust designs that can operate for long periods in a hostile underwater environment.
- Low dependence on ocean/river conditions – application of non-linear resonance permits useful energy to be extracted over a broad range of current speeds.
- The vortex shedding mechanism used by VIVACE is similar to the mechanism used by fish to propel in water faster than their muscle power allows. It is also a self-limiting phenomenon: an attempt to extract more energy than certain limit causes termination of synchronization and shutdown.

Vortex Induced Vibrations result from vortices forming and shedding on the downstream side of bluff bodies – such as cylinders and spheres - in a current. Such bodies are flexible or mounted on elastic supports. Vortex shedding alternates from one side to the other, thereby creating an oscillatory force, which may result in vibration of flexible structure. The VIV phenomenon is nonlinear as it is a fluid-structure interaction phenomenon. Fluid forces depend on structural dynamic response and vice versa. The primary manifestation of such nonlinearity is the synchronization phenomenon between vortex shedding and structural vibration. This synchronization range is as much as 50%-

60% plus/minus the natural frequency of the structure in still water. This means that VIVACE can produce useful energy over a very wide range of current velocities. Other ocean energy concepts are more restrictive and can only produce electricity within a narrow band of conditions, or require complex variable pitch turbines.

Even though VIV are being studied experimentally since 1963, all available tests focus either on small scale lab experiments or large scale field tests by the offshore industry aiming at suppressing VIV. The research carried in this project focuses for the first time in a totally different domain of VIV under high damping. The latter is induced back to the mechanical system as energy is harnessed.

The benefits to the public are obvious and numerous. All tests indicate that VIVACE is capable of extracting energy from ocean/river currents using a natural phenomenon without disturbing marine life or the environment. This technology is highly scalable and produces energy over a wide range of current speeds. These attributes allow energy to be derived from any flowing resource to perpetually power underwater sensors, stealthily supply electricity to surveillance equipment located on or near rivers/streams, and even power devices inside the human body using blood as the working fluid.

Project Description

1. Original project goals and objectives

Project Objective: The primary objective of the project is to demonstrate a laboratory scale VIVACE converter. The initial test were run with artificial damping to mimic an electrical generator. Once this test successfully showed uninterrupted nonlinear resonance with no “dead zones” over an expected range of velocities, an off-the-shelf generator was integrated. Data was gathered on the power take-off at different current speeds to assess efficiency. Then, key parameters were adjusted to determine if the efficiency could be improved. Other tests included extreme velocities. The goal of these tests is to demonstrate that vibrations and electrical generation can return after a disruption. In parallel with the technical tasks, Vortex Hydro Energy (VHE) conducted some commercialization activities as part of the proposed project. These include identification of a potential site for a VIVACE demonstration and a preliminary cost estimate.

2. Variance from original goals and objectives

Primarily the work conducted followed the original plan. The only variance was the elimination of subtask 3.3 – Debris Test. These experiments were replaced with additional high velocity and high damping experiments and due to the Low Turbulence Free Surface Water Channel test apparatus’ inability to handle debris. However, manual obstruction of the cylinder movement does indicate that oscillations will resume after a disruption.

3. *Discussion of work performed, hurdles overcome, findings, results and analysis, etc.*

Task 1: Experimentally Demonstrate Uninterrupted Nonlinear Resonance with No Dead Zones

Subtask 1.1: Design

VHE refined the engineering calculations, design parameters, and load profiles of the scale model VIVACE converter, and has designed the mounting structure, instrumentation, and completed the test plan. Work product includes m*, K, damping, and all design particulars, mechanical loads on the supporting structures, geometries, mechanical drawings, test plan document with load profiles, and instrumentation plan (potentiometers, data recording and processing, and video setup).

Subtask 1.2: Build

VHE acquired all parts, built up the mechanical subassemblies and fabricated in the MHL shop the scale model VIVACE converter called VIVACE Model I. This Model I been installed in the Low Turbulence Free Surface Water Channel of Marine Hydrodynamics Laboratory (MHL). VHE has installed the instrumentation for displacement and loads. A video camera system has been used to record cylinder motion and displacement.

Subtask 1.3: Test & Analyze:

VHE has performed numerous tests in the range of 0.1 – 1.3 m/sec (0.33-4.27 ft/sec) of current velocities. Even for a fixed stiffness value and for this first and rather crude Model I, we established a synchronization range of 0.5-1.05m/sec. The mass ratio m* used was 1.45. VHE analyzed the data and compared to theory. VHE defined the damping characteristics most favorable for stable VIVACE performance, and connected to Model I a commercial rotary generator with the appropriate torque-speed characteristics to provide the best damping.

Task 2: Assess Feasibility of Electrical Generation

The system was improved several times enabling a more efficient transmission of energy from the oscillating VIVACE cylinders to the generator. This process was completed as we moved from Model I to Model II and finally to Model III.

Subtask 2.1: Install

VHE installed a Power Take-Off (PTO) system, consisting of an off-the-self commercial rotary generator and transmission gear, onto the VIVACE Model I already installed in the laboratory. The generator is a small wind energy generator type, which provides acceptable efficiency at low RPM.

Subtask 2.2: Test & Analyze

VHE tested the scale model system in the Low Turbulence Free Surface Channel of MHL for mechanical VIV and PTO efficiency over the design operating range. Mechanical and electrical modifications were completed to achieve the target mechanical VIV efficiency of greater than 25%. The specific tests were the same as in

Subtask 1.3. Measurements of loads, displacements, damping, efficiency, and electrical output of the PTO system were achieved.

Task 3: Improve Efficiency & Test for Durability

Subtask 3.1: Optimize:

We manufactured installed and tested VIVACE Model II and Model III. Tests show peak efficiency of 30.73% and a Root Mean Square (RMS) efficiency of 21.73%. See figures below

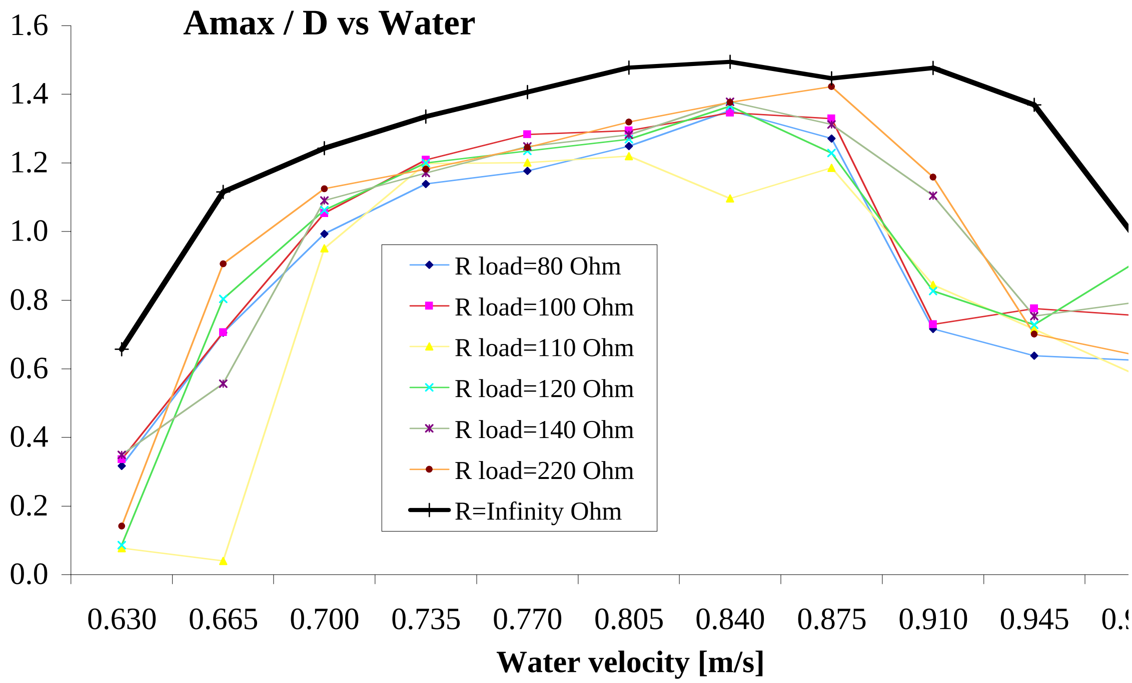

Figure 1: Normalized amplitude vs water velocity for different values of resistance. It is clearly seen that low resistance, meaning higher damping, suppresses the high VIV amplitudes

We use the symbol "A" for amplitude of oscillation of the nearly sinusoidal motion of the cylinder in VIV. Amplitude is non-dimensionalize it using "D" the cylinder diameter. For example, in Figure 1 for R=125 Ohm, the center of the cylinder in VIV reaches an amplitude of sinusoidal oscillation of A/D=1.35.

Please notice that in spite of the damping that we induce through the electrical resistance - so we can harness energy – in our tests, A/D reached values much higher than those reported in the literature. Without damping we observed amplitudes of A/D=2! We were really concerned about that until we found out that we are the only ones who carried tests in such a large facility that would allow Reynolds numbers around $(1\text{-}2)*10^5$. There is only one other recent paper from Exxon/Mobil, which shows such large A/D. We continued our work and realized that Reynolds number (Re) is very important and A/D depends strongly on Re; a conclusion that researchers had just started appreciating but cannot prove because of the limitations of their facilities. We will publish our results at the next IUTAM (International Union of Theoretical and Applied Mechanics) in July 2007.

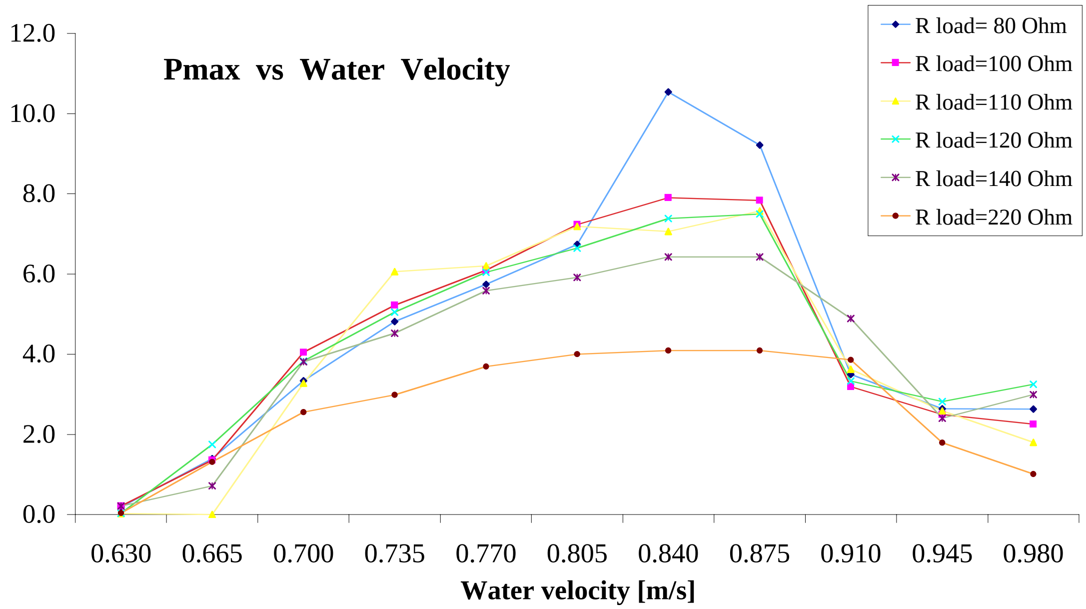

Figure 2: Generated power vs water velocity, for several resistance values

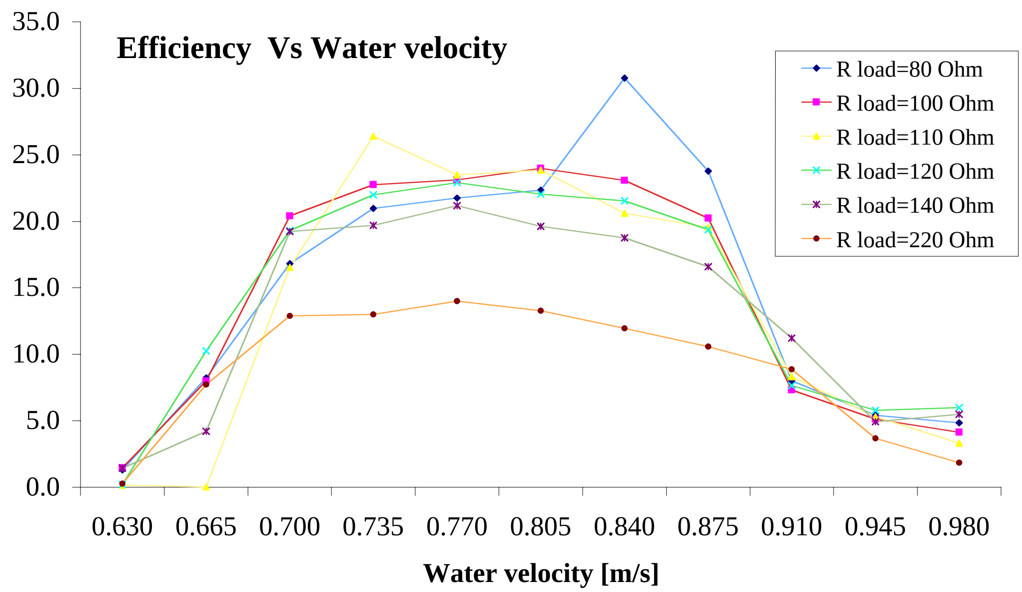

Figure 3: Peak efficiency (maximum power over the power in the stream of water) vs water velocity, for several resistance values. For a broad band of water velocity efficiency higher than 20% is maintained for R=100 Ohm.

What is even more impressive than the efficiency is the range of synchronization of the VIVACE Converter. In addition, we have achieved such a high efficiency by optimizing only the relation between the electrical load resistance to the mechanical damping.

Subtask 3.2: Extreme Velocity Test:

Numerous such tests were run on a regular basis as we did systematic tests from very low to very high velocities. Actually, very high speed tests prove to be less trying for VIVACE because on one hand they increase the in-line forces but on the other hand they take VIVACE out of the VIV range resulting in lower transverse load. In all cases the system went back to regular synchronization and routine performance with no problem whatsoever.

Subtask 3.3: Debris Test:

We tried a small number of debris tests and realized immediately that those are not as severe as expected and have minimal impact on VIVACE. Also, the Low Turbulence Free Surface Water Channel is not set-up to handle debris. So, we replaced those tests with the following. We reduced the mechanical damping by increasing the electrical resistance and let the amplitude of oscillation increase. The result was severe banging of the device gear casings on the stops we have. No damage was observed. After about 6 months of testing, we had to replace the bearings. It is not clear at this point if the bearings were damaged by those tests or they were worn down as they were not new when we started the tests. New bearings were purchased for Model III.

Subtask 3.4: Scale-up:

Scale up calculations were completed and published in. It should be pointed out that the two full papers that we published are major papers about 2-3 times the size of regular journal papers. The first one is 15 journal pages long. The second is 19 journal pages long.

Task 4: Commercialization and Development Planning

Subtask 4.1: Site Selection

- Discussed with Michigan's Department of Natural Resources (DNR) and others regarding using VIVACE devices in situations where old dams are earmarked for removal.
- Introduced the VIVACE concept to representatives at Consumers Energy, a subsidiary of CMS Energy, located in Jackson, Michigan. Consumers Energy operates multiple hydroelectric dams in the state and will likely work with VHE (and Michigan DNR) to find a suitable location for a field demonstration.
- Also engaged NextEnergy, a Michigan based non-profit corporation founded to enable the commercialization of energy technologies that positively contribute to economic competitiveness, energy security, and the environment.
- Ultimately, a site in the Detroit River near the Bell Isle bridge was selected as the best site for a VIVACE demonstration.

Subtask 4.2: Life-cycle Cost

- A cost estimate for a VIVACE ocean power plant, prepared by a team of graduate students at University of Michigan Engineering's department of Naval Architecture and Marine Engineering, was scrutinized to determine its usefulness for estimating the cost of a river energy converter.

- Information from a report prepared by Michigan Electric Capacity Need Forum was used to compare a variety of traditional and alternative electrical generating technologies on an economic basis. The table below shows the capital, operating and cost per kWh for select technologies. Also included is an assessment of VIVACE with projected capital and operating cost.

High Utilization Expected for VIVACE Eases Capital Cost Constraints

Technology	Capital Cost $/kW	Fixed O&M $/kW	Fuel Cost $/kWh	Variable O&M $/MWh	Capacity Factor	Cost per kWh $/kWh
Conventional Generation						
Pulverized Coal - Super Critical	1,437	43.60	0.011	1.70	85%	**0.041**
Nuclear	2,180	67.90	0.005	0.53	90%	**0.046**
Natural Gas Combined Cycle	467	5.41	0.043	2.12	45%	**0.062**
Alternative Generation						
Wind	1,200	156.43	0.000	-18.00	25%	**0.069**
VIVACE - Ocean Power Plant	3,000	70.72	0.000	0.00	90%	**0.055**

Note: 1. VIVACE capital cost need to be confirmed for river applications.
2. VIVACE operating cost taken from ocean power plant study, may be higher due to smaller scale of river installations, or lower from the move to freshwater

Subtask 4.3: Final Report

- Complete

4. Conclusions and recommendations for future work

Concept Development Conclusions

(1) A new concept for generation of clean and renewable energy from ocean/river currents has been introduced. An energy converter, nicknamed VIVACE (Vortex Induced Vibrations Aquatic Clean Energy) has been designed and tested. It extracts energy successfully and efficiently from fluid flow by strengthening rather than suppressing vortex shedding, enhancing rather than spoiling vortex shedding, and harnessing rather than suppressing VIV energy. In its simplest form a VIVACE Converter modulo consists of a rigid circular cylinder mounted on linear springs.

(2) Three gradually improved models – I, II, III – have been built and tested in the Low Turbulence Free Surface Water Channel of the University of Michigan.

(3) The VIVACE Converter appears to satisfy all requirements set by the California Energy Commission and the US DOE: it is unobtrusive to navigation, marine life, and coastal real estate; it is simple with all power, transmission, and electrical components sealed from the water environment; it is based on readily available offshore technology implying robustness and at least a 20 year life; it also has high energy density.

(4) The VIVACE Converter generates energy with high efficiency even at speeds as low as 0.5 knots, thus, making it possible to extract energy from resources that turbine and watermill technologies cannot. Turbines and watermills work efficiently in current velocities higher than 4knots.

(5) Additional advantages include consistency of current flow and its availability all year round; the broad range of synchronization, which allows efficient extraction of energy with minor and slow adjustment of basic design parameters such as the spring stiffness and induced damping; its ability to extract even more energy even in case of velocity surge to 5 knots and higher.

(6) The VIVACE Converter is scalable. The basic underlying phenomenon of vortex shedding behind a cylinder provides the same general wake characteristics at a lab scale of $Re=10^3$ to an island mountain scale of 10^{12} or higher.

(7) Due to the scalability of the VIV phenomenon, the scalability, modularity of a VIVACE Converter (many small cylinders can produce as much energy as fewer and larger cylinders), and its design flexibility the VIVACE Converter has a broad range of applications.

(8) Benchmarking with respect to conventional and alternative energy generation and wave energy converters appears very promising. The VIVACE Converter appears to be better than wave energy converters in the following ways: Its energy output per volume is 2-30 times higher; its energy output per footprint volume is 4-10 times higher, its energy output per weight is 2-3 times higher. In addition, the VIVACE Converter satisfies all DOE and California Energy Commission requirements for renewable energy devices.

(9) There is plenty of room for improvement of the VIVACE Converter at the modulo level: (i) Optimization of the hydrodynamics of VIV including vortex shedding mode under high damping and vortex strength enhancement and shedding phase (timing). (ii) Optimization of the range of synchronization and the amplitude of VIV under high damping. (iii) Optimization of the Power Take-Off system.

(10) There are two areas of promising improvement of the VIVACE Converter at the power plant level: (a) Optimize for the trade-off between complexity and high energy density. (b) Optimize the configuration of the array of VIVACE cylinders in the three-dimensional ocean space.

Model Test Conclusions

(11) A single modulo of the VIVACE Converter consisting of a circular cylinder mounted on elastic springs was tested in the Low Turbulence Free Surface Water Channel of the Marine Hydrodynamics Laboratory of the University of Michigan. The tests proved the concept and actually generated energy with high efficiency in spite of the rudimentary model design.

(12) Even though numerous experiments have been conducted in VIV since the early 1900's, the regime of applicability to the design of the VIVACE Converter had not been tested before. Specifically, for VIVACE to convert kinetic fluid flow energy to electricity, VIV has to be maintained under high damping. No one has tried before our work to conduct VIV tests under high damping.

(13) In a realistic ocean environment, Reynolds number is high for energy generation, which proved to be beneficial as the amplitude of VIV increases significantly for high Re, a regime scarcely tested before.

(14) We have proven with our most recent tests that VIV amplitude increases with Reynolds number. This is a conclusion that nobody was able to derive before. Only recently, a strong VIV research group at Caltech collected data supporting this conclusion but for rather low Reynolds numbers. Our results will be presented at the IUTAM 2007.

(15) A mathematical model was developed combining VIV with transmission via a gear-belt mechanism, a generator, and an energy harnessing electrical resistance. This model is compatible with the hydrodynamic model we developed.

(16) The mathematical model proved that measurements were consistent and accurate by comparing the measured harnessed power to the power calculated using data also collected during a particular test.

(17) The maximum peak efficiency achieved for the tested VIVACE modulo was $h_{\mathrm{Peak}} =$ 0.308. The corresponding integrated power efficiency in that particular test was $\eta_{\mathrm{VIVACE}} =$ 0.22 with a theoretical upper limit based on measurements of $\eta_{\mathrm{UL\text{-}VIVACE}}$ = 0.3663. Test velocity was U = 0.840m/sec = 1.63knots.

(18) The results show that the VIVACE Converter can convert kinetic energy to electricity with high efficiency even at low speeds where watermills and turbines cannot operate efficiently.

Recommendations of Future Work

The next step in development of the VIVACE Converter towards a market product is feasibility assessment. This includes five parts that generally can be performed in parallel. They include: (a) improving the VIVACE hydrodynamics, (b) conducting a preliminary environmental assessment, (c) doing a preliminary business feasibility assessment, (d) building a prototype, and finally (e) improving the design algorithm for VIVACE Converters.

(a) <u>Improve the VIVACE Hydrodynamics</u>

(i) Improve our understanding of the hydrodynamics of high damping VIV including vortex shedding, range of synchronization, wake structures, vortex phasing, self-limiting mechanism, etc. This information is essential for the design and control of commercial scale VIVACE devices.

(ii) Use LIF (Laser Induced Fluorescence), already installed in the Low Turbulence Free Surface Water Channel of the University of Michigan, to visualize vortex shedding, wake structures, and effect of proximity of wake to fee surface and bottom. Proximity to boundaries are required for the environmental assessment.

(iii) Design of an optimal power take-off strategy to convert the oscillating motion of VIVACE cylinders into electricity. Efficiently transforming the mechanical motion of VIVACE cylinders into power is a vital component of the technology's economic viability.

(iv) Numerical modeling of VIVACE. Even the best two commercial codes AcuSolve and FLUENT require calibration based on model tests to solve the flow past a cylinder in VIV since they actually use RANS. Also, the variety of VIVACE configurations does not allow for tests in all cases. Thus, a calibrated numerical model is mandatory in designing installations ranging from small-scale river power to multi-megawatt ocean power plants.

(b) Preliminary Environmental Feasibility Assessment

(v) Environmental assessment of a VIVACE river installation. Although it is believed that VIVACE is environmentally benign, evidence supporting this supposition will be useful in winning grants for further research and investment for product development.

(c) Preliminary Business Feasibility Assessment

(vi) Economic feasibility report detailing the viability of VIVACE installation and the business that will bring the technology to the market. The financial and business aspects of the technology must be understood to verify that VIVACE can produce energy in a cost effective manner and the company commercializing the technology is a viable venture worthy of investor attention.

(d) Build a VIVACE Prototype

Lab models have proven the concept and have produced very good results on the basis of which a VIVACE Converter can be built. Model tests can be continued and there is tremendous room for improvement. But to convince investors to support this invention and convert it to a product, we need to solve some routine engineering problems.

(vii) Design a 10kWatt rated VIVACE Converter.

(viii) Select a sealing method for all electronics, controls, and power-take-off system to be housed in the dry environment inside the supporting struts.

(ix) Design a power take off system. We have investigated rotary generators, linear generators, and hydraulic systems. The former is what we have used so far. Linear generators better fit VIVACE lab models. Hydraulics appear to be the best system for real life VIVACE converters.

(x) Design the marine foundation based on standard offshore engineering technology.

(xi) Fabricate the 10kWatt VIVACE Prototype at a marine engineering shop

(xii) Dry test the VIVACE Prototype for power-take-off, controls, sealing, strength, damping, weight, marine foundation.

(xiii) Launch the VIVACE Prototype in a river. A Detroit River location near the Bell Isle bridge has been identified at this point.
(xiv) Perform wet tests and measurements.
(xv) Verify preliminary environmental assessment performed with simulations and model tests

(e) Improve the Design Algorithm Based on the Above Results
The design of a VIVACE Converter is scalable, modular, and flexible. The same power output can be achieved by many small cylinders or fewer larger cylinders. Configuration of the occupied three-dimensional space can have different dimensions. Cylinders can be packed relatively close – about an order of magnitude closer than turbines. As results from studies (a)-(d) are generated the design algorithm can be improved by adding new constraints into the design optimization problem.

(xviii) Optimize for the trade-off between complexity and high energy density. Smaller cylinders are closer packed but increase the number of components. Tenfold increase in energy density has been calculated using smaller cylinders in denser formation as VIV is a highly scalable phenomenon.
(xix) Optimize the configuration of the array of VIVACE cylinders in the three-dimensional ocean space.
    i. Introduce financial constraints regarding minimum efficiency, installation cost, maintenance cost, operational cost.
    ii. Introduce environmental constraints regarding proximity to free surface and bottom boundary as well as flow changes.

Supplemental Information

Presentations:
(1) Tad Dritz and M. M. Bernitsas, "The VIVACE Converter" World's Best Technology (WBT) Showcase, Arlington, Texas, March 28-29, 2006. Selected as one of 25 technologies for a long presentation.

(2) Bernitsas, M. M., Y., Raghavan, K., Ben-Simon, Garcia, E. M.H., 2006, "VIVACE (Vortex Induced Vibrations Aquatic Clean Energy): A New Concept in Generation of Clean and Renewable Energy from Fluid Flow," 25th International OMAE Conference, Hamburg, Germany, June 4-9.

(3) Bernitsas, M. M., Ben-Simon, Y., Raghavan, K., Garcia, E. M.H., 2006, "The VIVACE Converter: Model Tests at High Damping and Reynolds Number Around 105," 25th International OMAE Conference, Hamburg, Germany, June 4-9.

(4) Tad Dritz, "Vortex Induced Vibrations Aquatic Clean Energy: A New Concept to Generate Clean and Renewable Energy from Ocean Currents," EnergyOcean 2006, San Diego, California, June 21, 2006

Abstracts:

(5) ABSTRACT: “The VIVACE Converter, a new concept in generation of clean renewable energy from fluid flow”, M. M. Bernitsas and T. A. Dritz, Energy Ocean 2006.

Papers:

(6) Bernitsas, M. M., Y., Raghavan, K., Ben-Simon, Garcia, E. M.H., 2006, “VIVACE (Vortex Induced Vibrations Aquatic Clean Energy): A New Concept in Generation of Clean and Renewable Energy from Fluid Flow,” 25th International OMAE Conference, , Hamburg, Germany, June 4-9.; and Journal of Offshore Mechanics and Arctic Engineering, ASME Transactions, to be submitted immediately after the Conference.

(7) Bernitsas, M. M., Ben-Simon, Y., Raghavan, K., Garcia, E. M.H., 2006, “The VIVACE Converter: Model Tests at High Damping and Reynolds Number Around 105,” 25th International OMAE Conference, Hamburg, Germany, June 4-9.; and Journal of Offshore Mechanics and Arctic Engineering, ASME Transactions, to be submitted immediately after the Conference

Appendix A

Final Task Schedule

Final Task Schedule

Task Number	Task Description	Task Completion Date				Progress Notes
		Original Planned	Revised Planned	Actual	Percent Complete	
1	Experimentally Demonstrate Uninterrupted Nonlinear Resonance with No Dead Zones	10/31/05	10/31/05	10/31/05	100%	Completed.
2	Assess Feasibility of Electrical Generation	11/30/05	1/31/06	1/31/06	100%	Completed.
3	Improve Efficiency & Test for Durability	2/28/06	2/28/06	2/28/06	100%	Completed.
4	Commercialization and Development Planning	3/31/06	2/28/06	3/31/06	100%	Completed.

Appendix B

Final Spending Schedule

Final Spending Schedule **Project Period:** mm/dd/yy to mm/dd/yy

Task	Approved Budget	Final Project Expenditures
Task 1 Demonstrate Nonlinear Resonance	13,000	9,926
Task 2 Assess Feasibility of Electrical Generation	20,000	23,827
Task 3 Improve Efficiency & Test for Durability	25,000	27,485
Task 4 Commercialization and Development Planning	10,000	6,762
Total	68,000	68,000
DOE Share	50,000	50,000
Cost Share	18,000	18,000

Appendix C

Final Cost Share Contributions

Final Cost Share Contributions

Funding Source	Approved Cost Share		Final Contributions	
	Cash	In-Kind	Cash	In-Kind
Vortex Hydro Energy		10,000		10,000
U of Mich. College of Engineering	3,000		3,000	
U of Mich. Hydrodynamics Lab		5,000		5,000
Total	3,000	15,000	3,000	15,000
Cumulative Cost Share Contributions				18,000

Appendix D

Energy Savings Metrics

Since VIVACE is an energy generating technology, and not a energy saving technology, this appendix has been modified.

One Unit of Proposed Technology:
VIVACE is highly scalable and capable of producing electricity for applications ranging from microhydro installation (<100 kW) to utility-scale hydropower projects (>10 MW). The size, weight and other specifics of various scale VIVACE installations can be found in the table below. For comparison purposes, a 10 MW river installation was selected. Assuming an average 3 knot current, this facility would require 1,314 cylinders each measuring 1 meter in diameter and having a length of 20 meters. The installation would weigh approximately 11,400 tons. Please note that the table below is for ocean installations, which can accommodate a draft (depth) of 15+ meters; river VIVACE installation will be configured to operate in shallower waters over a larger area.

VIVACE is Highly Scalable to Various Generation Needs

Scale	Power $P_{VIVACE\text{-}Har}$ (MW)	Number of Cylinders	D (m)	L (m)	h (m)	S (m^2)	W (ktons)
Giga	1000	32,849	2	40	60	1,497,335	1,775
Mega	100	6,570	2	20	30	258,998	159.0
Large	10	1,314	1	20	15	14,569	11.4
Medium	1	526	0.5	10	15	2,428	1.1
Small	0.1	328	0.2	4	5	92	0.10
Micro	0.05	657	0.1	2	5	45	0.05

One Unit of Current Technology:
The current hydropower technology is traditional hydroelectric dams. The generating potential, size/weight of the dam, and the amount of land that must be submerged for impounded water are site specific. However, an example of 10 MW dam was found on the internet for comparison. Below is the description of a hydroelectric project in Tripura, a province in northern India.

> A 30 metre high gravity dam was constructed across the river Gumti about 3.5 kilometres upstream of Tirthamukh in south Tripura district for generating 8.6 megawatts of power from an installed capacity of 10 MW. The dam submerged a valley area of 46 sq km. This was one of the most fertile valleys in an otherwise hilly state, where arable flatlands suitable for wet rice agriculture are extremely limited. Official records suggest 2558 families were ousted from the Gumti project area – these were families who could produce land deeds and were officially owners of the land they were ousted from. Unofficial estimates varied between 8000 to 10,000 families or about 60 to 70 thousand tribes-people displaced. (HIMAL – South Asia < http://www.himalmag.com/2004/may/perspective.htm>)

Discussion of Benefits:

Experimental results indicate that VIVACE can produce energy with a density of 0.322 kW/m³. For a 10 kW installation the water volume required is approximately 32,000 cubic meters. If the water depth is 2 meters, the area occupied is 16,000 square meters, or 0.016 square kilometers. This is very small when compared to the 46 square kilometers that were flooded by the Tripura dam, which necessitated the displacement of tens of thousands of people.

VIVACE installations also do not substantially disturb the flow of the river, allowing fish to swim both up and downstream while generating electricity. The same cannot be said of traditional hydroelectric dams, which dramatically change river ecosystems in pseudo-lake ecosystems upstream and starve the downstream environment of nutrients.

Although, VIVACE is seen to be generally advantaged over conventional hydroelectric projects, it does lack a few features offered by traditional dams. First, the impounded water has economic value for irrigation and recreation. Dams also regulate the flow of rivers, which can prevent flooding of downstream communities. VIVACE installation will not be capable of river control.

Market Penetration

Based on the projected development path for VIVACE, a commercial product will not be available until late 2009 or early 2010. So, the environmental benefits will not accrue in any substantial fashion until the next decade. However, by 2015 it is expected that river VIVACE installation will total over 700 MW. When compared to the composite U.S. electrical grid, the environmental benefits are substantial, as shown in the table below.

VIVACE Offers the Opportunity to Avoid Substantial Pollution

	700MW
Offset Resources	
Coal (ktons)	2,900
Natural Gas (BCF)	19
Avoided Pollution	
SOx (tons)	64,600
NOx (tons)	38,400
Particulate (tons)	25,600
Greenhouse Gases (equivalent ktons CO_2)	26,500

Notes 1. Offset resources based on U.S. average electricity generating mix
2. Avoided pollution from Franklin & Assoc. 1992 Report, Appendix A