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Final Scientific/Technical Report

Project Title: High Efficiency Driving Electronics
For General Illumination LED Luminaires

Prime Recipient:

Philips LED Systems

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Product Development Project

Subtask Priority Area: 4 – Electronics Development

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FINAL REPORT FOR DE-EE0000645

High Efficiency Driving Electronics for General Illumination LED Luminaires

Philips Lighting – LED Systems

This document consists of four sections. Section I provide an executive summary of the project. Section II covers the accomplishment of the project. Sections III summarize project activities for the entire period of funding. Section IV identifies the products developed under the award.

I. EXECURIVE SUMMARY:

New generation of standalone LED driver platforms developed, which are more efficient. These LED Drivers are more efficient ($\geq 90\%$), smaller in size (0.15 in³/watt), lower in cost (12 cents/watt in high volumes in millions of units). And these products are very reliable having an operating life of over 50,000 hours. This technology will enable growth of LED light sources in the use. This will also help in energy saving and reducing total life cycle cost of LED units.

Two topologies selected for next generation of LED drivers: 1) Value engineered single stage Flyback topology. This is suitable for low powered LED drivers up to 50W power. 2) Two stage boost power factor correction (PFC) plus LLC half bridge platform for higher powers. This topology is suitable for 40W to 300W LED drivers.

Three new product platforms were developed to cover a wide range of LED drivers: 1) 120V 40W LED driver, 2) Intellivolt 75W LED driver, & 3) Intellivolt 150W LED driver. These are standalone LED drivers for rugged outdoor lighting applications. Based on these platforms number of products are developed and successfully introduced in the market place meeting key performance, size and cost goals.

II. ACCOMPLISHMENT:

The first generation of the 150W/75W drivers were using Boost plus PWM half-bridge topology. Half bridge PWM was operating in low 20Kz frequency range. Therefore the size of magnetic components were large and correspondingly costs were also higher. Moreover the power circuit of 150W and 75W drivers were essentially same. These were optimized around 150W LED drivers. Therefore the size and cost of 75W drivers were relatively high. 40W drivers were designed around low frequency flyback. The efficiency of these drivers were low and size and cost were higher. In this project a new topology is developed which utilizes boost front end followed by LLC half bridge. This topology lends a smaller size lower cost and higher performance LED drivers. This topology is suitable for power rating from 40W to 300W. Value engineering of 40W driverbased on single stage flyback topology showed that an optimized design is possible for low power LED drivers up to 50W.

Three new product platforms were developed:

1. Intellivolt 75W Boost plus Half Bridge LED driver
2. Intellivolt 150W Boost plus Half Bridge LED driver
3. 120V 40W Flyback LED Driver

III. ACTIVITIES:

The project was divided into multiple phases as shown below.

Phase 1: Select Product Topology

In Phase 1, SMPS topologies were reviewed modeled and a prototype built and tested, in order to select the topology for the product to be built in Phase 2. Currently produced LED drivers are based on only a few of the possible topologies.

The tasks of Phase 1 include:

1. Review conventional hard-switched switch mode power supply(SMPS) topologies. Model, build and test the most promising topologies.
2. Review various resonant topologies. Model build and test key topologies:
 - Select the most promising topology for switch resonant SMPS studies. Model, build and test switch-resonant SMPS circuits.
 - Investigate LLC and LCC load-resonant topologies. Model, build and test circuits.
3. Compare the results from the hard switched and resonant topologies and select the final topology for the product.

Phase I was divided into two distinct phases.

Phase 1-A: The objective of the first phase (Phase 1-A) of the project is to investigate hard-switched, switch-resonant and load-resonant SMPS's, and select the best topology for the product.

Phase 1-B: The objective is to form a foundation of the platform for product development with the selected topologies.

Phase 2: Design and Release Driver Product

In the second phase, the topology selected during the first phase is used to develop LED driver products meeting the specifications.

The tasks of Phase 2 include:

1. Design the product to meet the specifications and requirements.
2. Perform tolerance analysis. The tolerance analysis helps to determine allowable variation in component values and hence the specifications on components. It also gives an indication of yields to be expected in manufacturing.
3. Conduct FMEA. The purpose of this step is to attempt to foresee potential field failures and take preventive action, if necessary.
4. Define and carry out a quality test plan. The quality test plan addresses topics such as:
 - Performance testing (output current/power, efficiency, power factor, harmonic distortion, etc)

- Stress testing (temperature, humidity, vibration, input variations)
 - Accelerated life testing
 - Lightening surge testing.
 - Electromagnetic compatibility (EMC) testing (FCC approbation)
 - Safety (UL approbation)
5. Conduct industrial engineering manufacturing build (IEMB) and pilot build runs. These sample runs, in contrast to any samples built at earlier stages (which are intended to verify technical performance), are to test manufacturing processes prior to product launch.

Project Timeline:

Each of the phases was divided into a number of milestones which had specific requirements associated with each segment.

Project Planning:

A plan was put together to address each of the three main aspects of the project – efficiency, size and cost. Since all of these are inter-dependent and potentially compete with each other, it was necessary to understand their interactions amongst themselves and then set up our strategy accordingly. For example, sometimes if a component needs to be chosen to get the best performance and small size, could end up being expensive. On the other hand, there are situations in which these constraints work together like when the driver is more efficient, the size can be made smaller. Generally smaller size means less material cost, less manufacturing and shipping cost per component, therefore should be lower cost. Some of these interactions were easier to identify and plan for, some other ones were realized during the development and then this was accommodated as and when any issues would arise. A few brain-storming sessions with the rest of the team helped to break down the broad objectives in to a specific action plan to help achieve the individual objectives.

1. Efficiency:

The following items were identified pertaining to improving the efficiency.

- Select the topology which has the best overall efficiency for an application like LED driver.
- Design the magnetic components appropriately to minimize winding losses and copper losses. The choice of switching frequency has a huge impact on the converter losses, so that is very crucial.
- Component selection for lowest loss components. Reducing the losses not only helps efficiency, but also improves the reliability of the component, thus improving the life of the product.

The efficiency is a parameter which sometimes tends to be in conflict with lower cost and smaller size. As an example, to make the magnetic components smaller, usually smaller cross-section of wire is used, which increases the losses and lowers efficiency. Therefore, special emphasis needs to be put on maintaining a reasonable efficiency, otherwise higher losses reduce the overall reliability of the product if the excess heat is not managed in the design.

Since efficiency was one of the metrics used right from the first phases of the project, all the decisions were influenced by a qualitative and quantitative analysis of how the efficiency is affected. The choice of the topology was made based on the highest efficiency over a wide operating range. Component size and selection of switching frequency range was made to get the most efficient implementation of the design. The low-side sensing for current control both on the output and the PFC sections was chosen with small sensing voltage, so that the power dissipation in the sensing resistors is very small. This makes the measurement very efficient and also very accurate since we can ignore errors arising from self-heating. The auxiliary power supply and the microcontroller clock frequency was set to a lower value and this allowed it to operate with less bias current and hence consume less power. Basically, low power consumption was used in all parts of the circuit.

2. Cost:

The cost reduction efforts were distributed along multiple aspects of product development. They can be broadly classified under the following categories. The bulk of the focus was on the electrical circuit aspect.

Electrical Circuit:

- (a) Looking for lower cost alternatives for most parts will obviously help to lower product cost.
- (b) Circuit topology choice based on lowest component count has the best chance of low cost.
- (c) Integrated control solutions with one IC with multiple functions, to reduce part count and save space on the PCB which becomes very crucial when the overall size is shrinking.
- (d) ICs with less peripheral components like integrated power supply, integrated gate MOSFET drivers are preferred, even though they might be slightly more expensive, the integration helps in the total cost and space savings, not to mention the improved noise immunity.

Mechanical components:

- (a) The housing dimension choice was not only based on our objective, but also tried to utilize an existing housing to save on tooling costs and efforts involved in the new housing design.
- (b) By using existing housing, the mechanical design is not in the critical path for the design.

Manufacturing and Packaging:

- (a) The circuit board dimensions and the processes for assembly are a major cost contributor and it is essential to look at every process to reduce the manufacturing cost.
- (b) Cost can also be managed better by using balanced processes, so one single process does not become the bottleneck.
- (c) The cost is also lowered by selecting the correct packaging kits and components.

3. Size:

As stated earlier, the size was predominantly based upon the available housings and input from the customers. Another factor is having enough surface area from all six faces to be able to dissipate about 8% to 10% of rated power with a reasonable self-temperature rise. The idea is that of all the heat generated inside the driver, depending upon the surface area and the emissivity of the surface of the driver, a portion of the heat is transferred to the surrounding air, while the remaining heat is left trapped in the driver housing and this heat causes the internals of the driver to heat up. Therefore, the internal components are always at a higher temperature than the temperature of the housing and that in turn is at a higher temperature than the surrounding air. Our product is designed to be operated from -40°C to 80°C case temperature which corresponds to about 55°C ambient temperature at the higher end. Hence, the surface area should be enough so as to dissipate enough heat to the surrounding air at 55°C ambient to ensure that all the internal components are within the specified design guidelines to guarantee full lifetime. If the temperatures of the internal components exceed the guidelines, then either the surface area needs to be larger, or the amount of heat generated needs to be decreased. So the size of the housing ties back to the efficiency in the end.

In our project, the size was decided based on the general expectation of how much area is needed to dissipate heat generated inside the driver with a 20°C to 25°C self-temperature rise on the housing for the material of the housing which is steel painted in black. Black color has a higher emissivity and hence was chosen over light color plating.

The size of the housing limits the size of the PCB and the components. The choice of the electrical circuit topology is therefore hinged upon selecting the circuit which will meet the space restrictions.

Milestones/Deliverables

Phase 1

The major Phase 1 milestones and associated success criteria are:

1. Select topologies for hard-switched/switch-resonant modeling and testing. Success criteria: Approximately 15 topologies selected for modeling.
2. Identify most promising hard-switched topology. Success criteria: Modeling, supported by experiment, results in high efficiency ($\geq 90\%$), high power factor (> 0.9) at specified full load conditions. There is potential to reach the cost and size specifications.
3. Identify most promising switch/load-resonant topology. Compare all topologies and select a product topology. Success criteria: Modeling, supported by experiment, results in high efficiency ($\geq 90\%$), high power factor (> 0.9) at specified full load conditions for the selected topology. There is potential to reach the cost and size specifications.
4. Design review. Success criteria: Design review passed. Estimated high-volume cost, efficiency, PFC & size meet specifications on sample units. Phase 1 ends and Phase 2 begins.

Phase 2

The major Phase 2 milestones and associated success criteria are:

1. Complete the design using the selected topology. Do an engineering sample-build of 50 or more units and evaluate & test.
2. Update the design as needed. Success criteria: Design is judged ready for IEMB run. Specifications are fully expected to be met by IEMB run.
3. IEMB run in factory completed. Success criteria: 100 or more units are built and pass the automatic testing performed during manufacturing (which verifies that the units meet specifications). Units are suitable for quality test plan execution.
4. Pilot run completed. Success criteria: 500 or more units are built and are tested using the automatic testing performed during manufacturing.
5. Product released. Success criteria: All specifications met. (Efficiency $\geq 90\%$, PF ≥ 0.9 , size $\leq 0.15 \text{ in}^3/\text{W}$, predicted lifetime $\geq 50,000$ hours). Yield of pilot run ($\geq 99.8\%$) is acceptable. Cost is acceptable. Manufacturing formally accepts project for production.

Implementation:

In the first phase of the project, an investigation was undertaken into the commonly used circuit topologies and configurations. This was mostly a theoretical exercise and the idea was to identify the most suitable candidates for an in-depth analysis which involved mathematical calculations as well as simulation and modeling and also lab prototypes to get all the necessary data to make a comparative analysis of the selected candidates. The most prominent metrics used included not only the main objectives, but also secondary metrics which helped to make the comparison very objective.

The topology tree in the figure below enlists the circuit topologies which were considered and eliminated based on theoretical analyses and in some cases by building lab prototypes to compare and evaluate. In the end, the Boost + LLC Dual Stage topology was seen to be the most appropriate choice to achieve the project objectives. Value engineering analysis of the Flyback shows that for low power LED drivers that is also a good option. The topology tree is shown below.

The following figure shows the architecture of the product based on boost plus LLC half bridge. The second picture shows a schematic representation of the LLC output stage.

Development of the Hardware:

The Project Start-Up (PSU) is when the key requirements in terms of electrical as well as the mechanical specifications and quality metrics were defined and agreed by Product Management, Development, Manufacturing, Supply Base Management and UL Approbation teams.

Existing housing were chosen which can accommodate all the components to enable quick cycle time. The choice of the dimension was also influenced by input from Product management about the preferences of the customers.

The circuit board dimensions were chosen based on the available volume of the housing and an optimal panel layout was defined to get the best panel utilization for lowest cost. The PCB panel choice was also influenced by which panel dimensions are already being used in the factory and this helps to save on the tooling cost for the clamps used to hold the panel in place during assembly and soldering processes. The PCB panel was selected to have 6 individual circuit boards to keep the individual product cost low.

Another contribution to the manufacturing cost is the PCB routing process. Usually most of the previous high power drivers have a 4-layer PCB which is made out of FR4 material which needs to be routed using an auto-router to separate the individual circuit boards. Also, the features in the PCB are routed and this adds cost due to the complicated tooling and equipment required. In these driver, we made a special effort to keep the PCB design in 2-layers, therefore the PCB material like Chem3 can be used which can be separated by cutting off the tabs which connect the PCB to the rest of the panels. This is a much cheaper process and by positioning the tabs in specific locations, new tooling is not required since we can use the tooling from existing products. Also, at the PCB supplier, the features in the PCB are done by means of a punching operation for the Chem3 type of material.

The optimal control IC solution was decided as the UBA2013T/N5 control IC from NXP which is used in extremely high volumes in E-fluorescent designs. This control IC is a resonant half-bridge control IC with integrated gate drivers and PFC control. It requires extremely low power for operation and was the best cost approach. The theoretical design for the LLC half-bridge was completed and when the first samples were developed, one of the limitations of the C2E IC came to the forefront. The C2E IC had fixed dead-time control for the half-bridge, which meant that the duration of time for which the LLC tank circuit gets to discharge and guarantee soft-switching is fixed. Also, there was a large tolerance ($\pm 12.5\%$) on this timing. The LLC circuit needs to be able to completely change state before the next switching cycle can begin and it was nearly impossible to design the tank circuit with this “fixed dead-time” control because the LED driver can be operated with a wide range of output voltages and currents and in each case, the mode of operation is different and a different time is required to ensure soft-switching. Therefore, it was clear that there was a need of a control IC solution which had “adjustable dead-time control”. The TEA1713T control IC was the component of choice. In addition to the adjustable dead-time control, it was actually adaptive, so the IC was able to change the dead time during the operation of the circuit in a simple but effective manner. From a fundamental perspective, this was the most important hurdle and once the TEA1713T IC was chosen, this problem was solved.

The LLC transformer design was also very critical because the highlight of the LLC tank circuit is that the leakage and magnetizing inductance can be combined into a single magnetic structure, which reduces component count. There was substantial amount of concern about the tolerances which affect the circuit operation, especially related to the LLC tank circuit, control IC switching frequency and the accuracy of the DC Bus. A number of simulations were developed to characterize the behavior, but there was a need for a more reliable means of predicting the behavior. A Design of Experiments (DoE) was developed with each of the parameters which affect the LLC tank operation and limit samples were developed along with appropriate test specifications to quantify the results. Based on the DoE data, adjustments were made to the circuit to guarantee that over all the specified tolerance ranges for the LLC components, related control IC parameters and output voltage and current set-points, the LLC stage will operate as expected and will provide the specified life of the product.

Another important aspect of quality control relates to the tolerance in the output current of the driver. Since the amount of light from the LEDs depends upon the amount of current driven through the LEDs, we specify a 3 sigma tolerance of 5% on the output current over temperature and part to part variations. Hence it was necessary for us to internally verify that we are able to meet this tolerance. Extensive mathematical modeling was used to do the Monte-Carlo analyses and get the expected theoretical distributions for the output current over the component and temperature variations. This data was corroborated by using data from the factory sample runs and engineering prototype builds to ensure that the distribution was as predicted by the theoretical equations.

The Boost and LLC Half-bridge design were completed and initial prototypes developed to verify operation as per the agreed specifications. Samples were sent to customers for initial feedback and also for internal qualification and agency approvals. Detailed design guides and reports were generated to enable quick and easy development of derivative models. In-depth tolerance calculations, CAD simulations and Design of Experiments were created and executed to make a robust design. Critical-to-quality parameters which were identified at the PSU stage were verified through calculations and experimentation. Other tools like Failure Mode Effect Analysis (FMEA) were used to make sure the product is sustainable after released for production.

Electromagnetic compatibility or EMC is an important requirement for the product and the product was designed to meet the FCC Part 15 Class A limits for conducted and radiated emissions in North America as well as the requirements for CISPR 15 Class A in Europe and APR. The resonant half-bridge converter provided a substantial improvement in the EMC over the earlier hard-switching design, thus greatly reducing the complexity of the EMC filtering circuit. This also helped to lower the cost. Europe / Asia region also requires the product to be compliant to IEC 61000 harmonic current limits and therefore, a THD improvement circuit was added to the design to help the driver operate within the specified limits in the specified output power range over the entire mains voltage range from 120Vac to 277Vac including 230Vac at 50Hz.

Next stage involved the creation of product documentation in SAP and execution of sample runs and Engineering Manufacturing builds to provide samples for internal as well as external validation of form, fit and function. A number of samples were also provided to the customers for their functional validation. A rigorous Quality Test Plan (QTP) was developed and followed which involved a combination of electrical, mechanical, thermal and agency tests to guarantee a reliable, safe and high quality product. Any issues encountered on any test were immediately resolved and the solution was re-tested. Test reports were created and filed in the internal project folders for future reference.

A. 75W LED Driver:

The first product developed in this family was the 75W 700mA driver for North American market. This was closely followed by development of the European model and more derivative models. In a period of eight months after the initial release, six derivative models were released, completing the 75W product portfolio for North America and Europe with family of drivers with 530mA, 700mA and 1A drive currents. This was possible because of all the initial effort in designing the platform to be extremely scalable.

Introduction:

This section outlines the development for a new generation of 75W LED drivers for outdoor application with optimal cost, size and performance in terms of efficiency. The first generation of the 75W drivers was basically a 150W driver based on the Boost + PWM half-bridge topology which was operated at 75W with some modifications, but in the same physical dimension and approximately the similar price point which made it not very attractive to the market. There was a need for a more efficient, smaller and lower cost LED driver designed for a 75W power level especially with the efficacy of the LEDs getting better, which meant for the same amount of light, the amount of electrical power required was less.

Objective:

The objective is to design and produce the first of a new generation of 75W LED drivers which will be switch-mode power supplies, similar to the existing LED drivers. They will be based on Boost + LLC half bridge, circuit topology to yield higher efficiency ($\geq 90\%$), smaller size than existing 75W Driver and lower cost.

Efficiency Target: $\geq 90\%$

Size Target: 11.25 in³ volume for a 75W Product

Cost Target: \$0.12 / Watt, which means \$9.00 for a 75W Product

Size Reduction

The first generations of 75W drivers were in the same dimension as the 150W, which was 55mmX210mmX36mm (about 26.6 in³) while the second generation of the product was 55mmX135mmX36mm (about 17.10 in³) which was about a 36% size reduction. The picture below shows the comparison of the size of the housing and the second picture shows the actual 150W and 75W circuits to provide a scale reference.

This enabled the product to go from 0.355 in³/ Watt to 0.228in³/ Watt. The choice of the housing was based on re-using an existing housing to avoid additional mechanical development and tooling costs.

Cost Reduction

By making the driver size smaller overall and also a reduction in the EMI filtering required thanks to the resonant switching circuit, a substantial cost reduction of > 30% was achieved in the second generation of the 75W driver. The cost has gone down by another 10% in last year and is expected to continue to become lower as the volumes increases. This is due to reduction in the cost of the individual components and also reduction in the manufacturing cost with the higher volumes.

Efficiency

The efficiency target was set to maintain the efficiency higher than 90%. The following chart shows a comparison in the efficiency between the 75W PWM based first generation of products and also 75W LLC based second generation of products both measured at 120V input. At 277V input, the efficiency is better than at 120V.

The chart shows that even though both the first and second generation products start at efficiency > 90%, the efficiency for the PWM driver drops substantially across the load range. The new generation with the LLC driver not only maintains > 90% efficiency, it actually gets better and higher than 91%.

In addition to the above, the following were other improvements / enhancements on the new product platform.

Electromagnetic Interference

CISPR15 TV Line and Neutral EMC

CISPR15 TV Line and Neutral EMC

The pictures above show the improvement in the EMI generated by the driver. The red marking on the 75W PWM driver spectrum indicates the areas where the EMI margin was low. The corresponding scan for the 75W LLC driver shows not only improvement in margin in those areas, but also a 10 to 15 dB

improvement across the board with much cheaper EMI filtering and a 2-layer PCB layout versus a 4-layer in the original designs which also contributes to cost reduction.

Additional Features

The first generation 75W drivers were dimmable drivers without a microprocessor. On the 75W LLC driver, a microprocessor was added which enabled us to add a number of features, some which improved our product offering making it more attractive for the customer. The figure below gives a quick summary.

Rset Interface for customer to set the full load current at any point on the defined Rset curve

Thermal Feedback using NTC thermistor to reduce output current in case of excessive temperature on the LED module

Feature Enhancements
using Microcontroller

Precise adjustment of the dimming curve from 1V-8V and precise current in the dimming leads to enable the use of resistor for dimming

Shutdown the driver by applying 15V at the dimming leads and very low standby power in shutdown mode (<200mW)

PRODUCTS DEVELOPED

Five different 75W LED driver models were developed using this 75W platform. As an example, the picture below shows the completely assembled product for the 75W 1A driver. This version is the one with only dimming and designed for NA market only.

Highlights:

- The Boost PFC input stage provides a stable DC Voltage output while giving excellent power factor, THD and harmonics performance.
- The mains filter helps in reducing the supply current harmonics and the conducted and radiated Electromagnetic Interference.
- Resonant power stage (LLC) allows for extremely low switching losses and low EMI generated, helping both the efficiency and cost.
- Half-bridge circuit + LLC converter provides a regulated DC output to the LEDs in the form of a constant current.
- A single control IC does the function of controlling the Boost PFC and LLC stage which reduces the chip count. The control IC of choice in this case was the TEA1713T IC from NXP.
- This control IC has an integrated high-voltage start-up supply which eliminates the need for an additional low-voltage supply by means of a buck or flyback type converter.
- The TEA1713T also has integrated low and high-side FET gate drivers which save the need for additional gate driver IC.
- TEA1713T had adaptive non-overlap time control which is crucial for the LLC resonant converter to get soft-switching always without the risk of capacitive mode
- The TEA1713T has a number of different protection features which when set appropriately allow the driver to be protected against misapplication like short circuit or open circuit on the output.
- Internal thermal protection folds the output current back in the event of over-temperature.
- A microprocessor was added on the secondary-side which sets a control reference to the current loop in response to different interfaces like RSET, external RNTC, 0-10V Dimming and internal thermal protection to set the LED current.

Key Benefits

The key benefits of the final product can be summarized as below.

“The reliable and flexible solution for energy-efficient LED outdoor lighting applications ”

Future Scope

Size: The dimension of the housing that we selected was based on reusing an existing housing and also input from customers that they expected the product to be the same height and width as the 150W, just shorter in length. In reality, the product could be made shorter in height. This will not only make the volume smaller, but also improve the thermal connection from the components to the housing and improve the overall performance.

Cost: Since the product is still new, as mentioned earlier the cost will be lower in the future as the product gains popularity and volume increases. At extremely high volumes (in the order of a million units each year or higher), the cost may drop by as much as 35% which will help us to reach the initial objective of \$0.12/Watt. This will also include some optimization of features, since at high volume; customers may not need all the features designed into the product. In fact, a fixed output product derived from this driver today will already be a cost reduction of at least 18%. So the expectation that we can get overall cost reduction of 35% at high volume is fairly realistic.

Efficiency: The efficiency is already > 90% and at that point, the “fixed losses” become dominant meaning the conduction losses in diodes and MOSFETs. The driver was designed to be able to operate with flexible input voltage and also be able to serve a 2:1 output voltage window. There is further optimization possible by making this dedicated to a fixed line voltage and making the output voltage range narrower which is possible when there is a high volume demand for a certain application. This would not only help the efficiency, but also some of the components may become cheaper since they do not need to be rated for the full voltage / current.

B. 150W LED Driver:

Development of the Hardware:

The Project Start-Up (PSU) is when the key requirements in terms of electrical as well as the mechanical specifications and quality metrics were defined and agreed by Product Management, Development, Manufacturing, Supply Base Management and UL Approbation teams.

An existing housing was chosen in the dimension 55mmX210mmX36mm to enable quick cycle time. The choice of the dimension was also influenced by input from Product management about the preferences of the customers.

The circuit board dimensions were chosen based on the available volume of the housing and an optimal panel layout was defined to get the best panel utilization for lowest cost. The PCB panel choice was also influenced by which panel dimensions are already being used in the factory and this helps to save on the tooling cost for the clamps used to hold the panel in place during assembly and soldering processes. The PCB panel was selected to have three individual circuit boards to keep the individual product cost low.

Another contribution to the manufacturing cost is the PCB routing process. Usually most of the drivers have a 4-layer PCB which is made out of FR4 material which needs to be routed using an auto-router to separate the individual circuit boards. Also, the features in the PCB are routed and this adds cost due to the complicated tooling and equipment required. In this driver, we made a special effort to keep the PCB design in 2-layers, therefore the PCB material like Chem3 can be used which can be separated by cutting off the tabs which connect the PCB to the rest of the panels. This is a much cheaper process and by positioning the tabs in specific locations, new tooling is not required since we can use the tooling from existing products. Also, at the PCB supplier, the features in the PCB are done by means of a punching operation for the Chem3 type of material.

The optimal control IC solution was decided as the UBA2013T/N5 control IC from NXP which is used in extremely high volumes in E-fluorescent designs. This control IC is a resonant half-bridge control IC with integrated gate drivers and PFC control. It requires extremely low power for operation and was the best cost approach. The theoretical design for the LLC half-bridge was completed and when the first samples were developed, one of the limitations of the C2E IC came to the forefront. The C2E IC had fixed dead-time control for the half-bridge, which meant that the duration of time for which the LLC tank circuit gets to discharge and guarantee soft-switching is fixed. Also, there was a large tolerance ($\pm 12.5\%$) on this timing. The LLC circuit needs to be able to completely change state before the next switching cycle can begin and it was nearly impossible to design the tank circuit with this “fixed dead-time” control because the LED driver can be operated with a wide range of output voltages and currents and in each

case, the mode of operation is different and a different time is required to ensure soft-switching. Therefore, it was clear that there was a need of a control IC solution which had “adjustable dead-time control”. The TEA1713T control IC was the component of choice. In addition to the adjustable dead-time control, it was actually adaptive, so the IC was able to change the dead time during the operation of the circuit in a simple but effective manner. From a fundamental perspective, this was the most important hurdle and once the TEA1713T IC was chosen, this problem was solved.

The LLC transformer design was also very critical because the highlight of the LLC tank circuit is that the leakage and magnetizing inductance can be combined into a single magnetic structure, which reduces component count. There was substantial amount of concern about the tolerances which affect the circuit operation, especially related to the LLC tank circuit, control IC switching frequency and the accuracy of the DC Bus. A number of simulations were developed to characterize the behavior, but there was a need for a more reliable means of predicting the behavior. A Design of Experiments (DoE) was developed with each of the parameters which affect the LLC tank operation and limit samples were developed along with appropriate test specifications to quantify the results. Based on the DoE data, adjustments were made to the circuit to guarantee that over all the specified tolerance ranges for the LLC components, related control IC parameters and output voltage and current set-points, the LLC stage will operate as expected and will provide the specified life of the product.

Another important aspect of quality control relates to the tolerance in the output current of the driver. Since the amount of light from the LEDs depends upon the amount of current driven through the LEDs, we specify a 3 sigma tolerance of 5% on the output current over temperature and part to part variations. Hence it was necessary for us to internally verify that we are able to meet this tolerance. Extensive mathematical modeling was used to do the Monte-Carlo analyses and get the expected theoretical distributions for the output current over the component and temperature variations. This data was corroborated by using data from the factory sample runs and engineering prototype builds to ensure that the distribution was as predicted by the theoretical equations.

The Boost and LLC Half-bridge design were completed and initial prototypes developed to verify operation as per the agreed specifications. Samples were sent to customers for initial feedback and also for internal qualification and agency approvals. Detailed design guides and reports were generated to enable quick and easy development of derivative models. In-depth tolerance calculations, CAD simulations and Design of Experiments were created and executed to make a robust design. Critical-to-quality parameters which were identified at the PSU stage were verified through calculations and experimentation. Other tools like Failure Mode Effect Analysis (FMEA) were used to make sure the product is sustainable after released for production.

Electromagnetic compatibility or EMC is an important requirement for the product and the product was designed to meet the FCC Part 15 Class A limits for conducted and radiated emissions in North America as well as the requirements for CISPR 15 Class A in Europe and APR. The resonant half-bridge LLC converter provided a substantial improvement in the EMC over the earlier hard switching design, thus greatly reducing the complexity of the EMC filtering circuit. This also helped to lower the cost. Europe / Asia region also requires the product to be compliant to IEC 61000 harmonic current limits and therefore, a THD improvement circuit was added to the design to help the driver operate within the specified limits in the specified output power range over the entire mains voltage range from 120V_{AC} to 277V_{AC} including 230V_{AC} at 50Hz.

Next stage involved the creation of product documentation in SAP and execution of sample runs and Engineering Manufacturing builds to provide samples for internal as well as external validation of form, fit and function. A number of samples were also provided to the customers for their functional validation. A rigorous Quality Test Plan (QTP) was developed and followed which involved a combination of electrical, mechanical, thermal and agency tests to guarantee a reliable, safe and high quality product. Any issues encountered on any test were immediately resolved and the solution was re-tested. Test reports were created and filed in the internal project folders for future reference.

Difficulty in the design came in the form of creating a reliable LLC transformer for this design. Several attempts to increase the reliability of the transformer required much time for environmental testing and delayed the release process until a suitable solution was found. The initial release was with a more expensive transformer than initially planned for and an immediate cost reduction effort was begun to reduce the cost. This resulted in a cost reduction of \$0.92 that is in the process of being phased in.

The first product developed in this 150W family was the 150W 700mA_{DC} global driver capable of being used for the Asian Pacific, European and North American markets. A second derivative 150W model operating at 1050mA_{DC} is currently in the design process.

Achievements:

The achievements have been classified under the three main objectives for the 150W driver which we started with.

Size

The first generation of 150W LLC drivers is in the same dimension as the previous 150W driver, which is 55mmX210mmX36mm (about 26.6 in³). Although no change was made to the size of the housing the picture below shows the housing and the comparison of the two 150W driver board assemblies (PWM Hard switched and LLC resonant) to indicate the reduction in components used.

Cost Reduction

By reducing the amount of components needed in the overall design and also a reduction in the EMI filtering required thanks to the resonant switching circuit, a substantial cost reduction of > 25% was achieved in the second generation of the 150W driver. This resulted in a cost of \$0.12/Watt. This was the cost of the product at the time of release to limited production. Since the last year, the manufacturing and component cost has reduced further resulting in \$0.1133/Watt due to reduced component costs and increase in manufacturing efficiency. Cost reductions to some of the magnetic components are in the process of being phased into the design and will reduce the cost in future and

help achieve cost of \$0.10/Watt. This is due to reduction in the cost of the individual components and also reduction in the manufacturing cost with the higher volumes.

Efficiency

The efficiency target was set to maintain the efficiency higher than 91.0%. The following chart shows the efficiency of the 150W LLC based driver measured at a 120V_{AC} input. The chart shows that the new generation with the LLC driver maintains > 91% efficiency across the load range.

In addition to the above, the following were other improvements / enhancements on the new product platform.

Electromagnetic Interference

The pictures below show the EMI generated by the 150W LLC driver operating at both 120V_{AC} and 277V_{AC}. The conducted EMI scan for the driver shows a 30plus dB margin to specification under the worst case fully loaded condition at 120V_{AC} operation and 15 plus db margin at 277V_{AC} operation. This is a 10 to 15 dB improvement over the existing hard switched topology with the benefits of using a less expensive EMI filter and using a two copper layer PCB versus a four copper layer PCB as required in the original hard switched product.

FCC 47 Part 15 TV Line & Neutral

Line Conducted EMI – 120V_{AC} with a 150W LED Load (700mA_{DC} and 214V_{DC})

CISPR15 CDN M2 or M3

Radiated EMI – 120V_{AC} with a 150W LED Load (700mA_{DC} and 214V_{DC})

Note: The graph shown is plotted to CISPR limits. The FCC limits are higher than the limits shown.

FCC 47 Part 15 TV Line & Neutral

Line Conducted EMI – 277V_{AC} with a 150W LED Load (700mA_{DC} and 214V_{DC})

CISPR15 CDN M2 or M3

Radiated EMI – 277V_{AC} with a 150W LED Load (700mA_{DC} and 214V_{DC})

Note: The graph shown is plotted to CISPR limits. The FCC limits are higher than the limits shown.

Power Factor Correction:

The picture below shows the power factor of the 150W LLC driver operating at 120V_{AC}, 230V_{AC} and 277V_{AC} operating under the worst case fully loaded condition (700mA_{DC} and 214V_{DC}). The requirement we set is that the power factor must be maintained above 90% at half load (75W) under all input voltage conditions.

Additional Features

The first generation LLC 150W drivers were intended to be fixed output drivers. On the 150W LLC driver as released, a PWM dimming circuit and external power supply were added which improved our product offering making it more attractive for the customer. This adds approximately a one dollar addition to the cost of the product and this cost is not reflected in the cost summary previously noted. The figure below gives a quick summary of the features as added. A graph showing the dimming feature performance is also included below.

External Power Supply: +5VDC 200mA 1W power supply allowing for an external control interface to be powered

Output Dimming: Precise adjustment of the dimming curve from 10 - 100% light output using a 0 - 100% duty cycle PWM signal as external input

PRODUCTS DEVELOPED

The following product platforms are released from the 150W project.

- Global 150W dual stage (PFC+LLC) with external +5VDC power supply and PWM dimming interface

The technology developed in this program is also being developed into a 150W 1050mA_{DC} driver with external +5VDC power supply and PWM dimming interface. Circuit design and component elements from this design are currently being used in a number of other product platforms.

The picture below shows the completely assembled product for the global 150W driver with external +5VDC power supply and PWM dimming interface.

Highlights:

- The Boost PFC input stage provides a stable DC Voltage output while giving excellent power factor, THD and harmonics performance.
- The mains filter helps in reducing the supply current harmonics and the conducted and radiated Electromagnetic Interference.
- Resonant power stage (LLC) allows for extremely low switching losses and low EMI generated, helping both the efficiency and cost.
- Half-bridge circuit + LLC converter provides a regulated DC output to the LEDs in the form of a constant current.
- A single control IC does the function of controlling the Boost PFC and LLC stage which reduces the chip count. The control IC of choice in this case was the TEA1713T IC from NXP.
- This control IC has an integrated high-voltage start-up supply which eliminates the need for an additional low-voltage supply by means of a buck or flyback type converter.
- The TEA1713T also has integrated low and high-side FET gate drivers which save the need for additional gate driver IC.
- TEA1713T had adaptive non-overlap time control which is crucial for the LLC resonant converter to get soft-switching always without the risk of capacitive mode
- The TEA1713T has a number of different protection features which when set appropriately allow the driver to be protected against misapplication like short circuit or open circuit on the output.
- Internal thermal protection folds the output current back in the event of over-temperature.
- An external +5VDC power supply and PWM dimming interface were added to enhance the product for customer use.

Key Benefits

The key benefits of the final product can be summarized as below.

“The reliable and flexible solution for energy-efficient LED outdoor lighting applications ”

Flexible

- Choice of output current
- Reduced SKU complexity and simplified logistics management
- Quicker time-to-market for LED luminaire manufacturers

Energy efficient

- 1-10V dimming protocol
- Over 91% operating efficiency

Highly reliable

- Robust specifications for moisture, vibration and extreme temperature protection
- Module Temperature protection for reliable luminaire life

Designed for Outdoor lighting

- Best energy efficiency
- Future-proof wrt LED efficacy upgrades

Future Scope

Size: The dimension of the housing that we selected was based on reusing an existing housing and also listening to input from customers that they expected the product to be the same height and width as the previous 150W product. No housing change is expected for the 150W products in the near future.

Cost: Since the product is still new, the cost will be lower in the future as the product gains popularity and volume increases. At extremely high volumes (in the order of a million units each year or higher),

the cost would drop by as much as 10% (only a cost drop of 6.5% is needed to reach the initial objective of \$0.10/Watt for a fixed output product derived from this driver).

Efficiency: The efficiency is already > 91.0% and at that point, the “fixed losses” become dominant meaning the conduction losses in diodes and MOSFETs. The initial 150W driver was designed to be able to operate with flexible input voltage (global) and also be able to serve a 2:1 output voltage window. There is further optimization possible by making this dedicated to a fixed line voltage and making the output voltage range narrower which is possible when there is a high volume demand for a certain application. This would not only help the efficiency, but also some of the components may become cheaper since they do not need to be rated for the full voltage / current.

C. 40W LED Driver:

Introduction:

Outlined in this report is the development for the new generation of the 40W LED driver for outdoor application with optimal cost, size and performance in terms of efficiency.

In the low power lighting applications cost is a dominant issue. Thus, the 40W driver was based on a single stage Flyback topology, resulting in a reduced complexity and cost. Further the size reduction would be an added advantage as the driver can be used in more applications.

Objective:

The objective is to design and produce the first of a new generation of the above mentioned 40W LED driver which will be switch-mode power supplies, similar to the existing LED drivers. It will be based on the single stage flyback circuit topology to achieve the size, cost and performance goals.

Efficiency Target: = 90%

Size Target: 7 in³ volume

Cost Target: \$0.12 / Watt, which means \$4.80 for a 40W Product (+ \$0.5 for dimming)

Implementation:

In order to meet the cost and size objectives, the single stage flyback topology was chosen. The following figure shows the architecture of the product.

Development of the Hardware:

The Project Start-Up (PSU) is when the key requirements in terms of electrical as well as the mechanical specifications and quality metrics were defined and agreed by Product Management, Development, Manufacturing, Supply Base Management and UL Approbation teams.

In the beginning the plan was to use an existing plastic housing with the dimensions of 132mmX34.2mmX25mm. But later due to heat and dissipation constraints the decision to move to a metal housing was made. In order to enable quick cycle time an existing metal can with the dimensions of 125mmX42.5mmX29mm was chosen. The choice of the dimension was also influenced by input from Product management about the preferences of the customers.

The circuit board dimensions were chosen based on the available volume of the housing and an optimal panel layout was defined to get the best panel utilization for lowest cost. The PCB panel choice was also influenced by which panel dimensions are already being used in the factory and this helps to save on the tooling cost for the clamps used to hold the panel in place during assembly and soldering processes. The PCB panel was selected to have 8 individual circuit boards to keep the individual product cost low.

The optimal control IC solution was decided as the L6562D control IC from ST which is used in extremely high volumes in other designs at Philips. This control IC is a transition mode PFC controller with integrated gate drivers and PFC control. It requires extremely low start up and quiescent current for operation and was the best cost approach. The single stage flyback design has been tried and tested multiple times at Philips, and this was an effort to make it more efficient and cost effective. Thus, when we got the first boards we didn't see any surprises with respect to the design.

The critical components like the transformers and the inductors which can be major source of cost savings, were bought from vendors who could provide us with the best cost as well as performance.

Once the design was completed the initial prototypes developed which were later tested to verify operation as per the agreed specifications. Samples were sent to customers for initial feedback and also for internal qualification and agency approvals. Detailed design guides and reports were generated to enable quick and easy development of derivative models. In-depth tolerance calculations and CAD simulations were created and executed to make a robust design. Critical-to-quality parameters which were identified at the PSU stage were verified through calculations and experimentation.

Electromagnetic compatibility or EMC is an important requirement for the product and the product was designed to meet the FCC Title 47 Part 15 Class A limits for conducted and radiated emissions in North America. Lighting surge is another important requirement, for which the product met a 3KV surge rating (per IEEE C62.41.2.2002).

Next stage involved the creation of product documentation in SAP and execution of sample runs and Engineering Manufacturing builds to provide samples for internal as well as external validation of form, fit and function. A number of samples were also provided to the customers for their functional validation. A rigorous Quality Test Plan (QTP) was developed and followed which involved a combination of electrical, mechanical, thermal and agency tests to guarantee a reliable, safe and high quality product. Any issues encountered on any test were immediately resolved and the solution was re-tested. Test reports were created and filed in the internal project folders for future reference.

Achievements:

The achievements have been classified under the three main objectives which we started with.

Size Reduction

The older design of the 40W was in a plastic housing with dimensions 88.98mmX82.98mmX37.97mm (about 17.1in³) while the current design was designed in a chassis with dimensions of 125mmX42.5mmX29mm (about 9.4in³). Thus, the total size reduction achieved was about 45%. The picture below shows the comparison of the size of the housing and the second picture shows the new and old 40W PCB's

This enabled the product to go from $0.43\text{in}^3/\text{Watt}$ to $0.24\text{in}^3/\text{Watt}$. The choice of the housing was based on re-using an existing housing to avoid additional mechanical development and tooling costs.

Cost Reduction

By making the driver size smaller overall and also using cost effective components a substantial cost reduction of $\sim 33\%$ was achieved in the new design of the 40W driver. The cost is expected to continue to become lower as the volumes increases. This is due to reduction in the cost of the individual components and also reduction in the manufacturing cost with the higher volumes.

Efficiency

The efficiency target was set to maintain the efficiency at $\sim 90\%$. The efficiency of the original 40W driver was about 83% which was improved to 89% in this new design. With some more optimization the efficiency target of 90% can be met.

In addition to the above, the following were other improvements / enhancements on the new product platform.

Additional Improvements

Size: The dimension of the housing that we selected was based on reusing an existing housing. In reality, the product could be made shorter in all the dimensions. This will not only make the volume smaller, but also improve the thermal connection from the components to the housing and improve the overall performance.

Cost: Since the product is still new, the cost will be lower in the future as the product gains popularity and volume increases. At high volumes (in the order of a million units each year or higher), the cost may drop by as much as 30% which will help us to reach the initial objective of $\$0.12/\text{Watt}$ and exceed it. This will also include some optimization of features, since at high volume; customers may not need all the features designed into the product (like dimming)

Efficiency: The efficiency is ~ 89% and at that point, the “fixed losses” become dominant meaning the conduction losses in diodes and MOSFETs. By optimizing the losses in the driver better, the goal of 90% can be achieved easily.

IV. PRODUCTS DEVELOPED:

Three new products were developed under this award, based on the three new platforms:

1. 120V 40W 700mA Dimming LED Driver
2. Intellivolt 75W 700mA Dimming LED driver
3. Intellivolt 150W PWM dimming LED driver

Several other models were developed later on using these platforms. This technology was later on also used to develop two new programmable LED driver platforms and number of products on these platforms.