(12) **CORRECTED EUROPEAN PATENT SPECIFICATION**

(54) **ADAPTIVE CONTROL OF CAPACITIVE LOAD**

ADAPTIVE STEUERUNG DER KAPAZITIVEN LAST

COMMANDE ADAPTATIVE DE CHARGE CAPACITIVE

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(56) References cited:
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Description

[0001] The invention deals with a method and a device for driving a capacitive load, preferably a piezoelectric load and/or a micro electro mechanical system (MEMS), even more preferably when the capacitive load is a speaker. Embodiments of the invention allow an advantageous control of the voltage and/or current of a capacitive load driver in a manner that limits the introduction of artefacts in a driving signal.

Prior art

[0002] Piezoelectric components are becoming more common in various electronic devices. As an example, a piezoelectric component can be used to generate haptic vibrations and/or a speakers in electronic devices such as mobile phone, tablets, PC, etc. Similarly, MEMS devices are increasingly being used as sensors, such as acceleration sensors, or actuators.

[0003] Piezoelectric components and MEMS devices are often seen by a driver, in first approximation, as a capacitive load. This often results in a low impedance. Values under 8 Ohm are for instance common, especially for high frequency signal content. This, in turn, requires a very large current compared to higher impedance loads.

[0004] Moreover, in particular in mobile devices, capacitive loads are typically powered by the system battery, whose voltage for a 1S cell generally ranges from 3V to 5V. Common peak voltages when driving a capacitive load - such as for instance a PZT thin film or a MEMS micro speaker - can be higher than 20V.

[0005] Therefore, a boost converter is required to raise the battery voltage up to the needed driving level. The current drawn from the battery can then be several times larger than the instantaneous current flowing into the capacitive load.

[0006] Thus, a proper control of voltage and/or current should be implemented to avoid triggering protections and/or reaching saturation of one or more components. In particular, various kind of protection circuits can be implemented in the driver, the boost converter, or in the battery itself, to limit voltage and current. Intervention of such protection circuits can generate artefacts in the signal driving the load, or even cause one or more parts of the circuitry to shut down for prevention. Similar situation arise when one or more component along the driving chain saturates.

[0007] Figure 1A schematically illustrates a circuit 1000A for driving a capacitive load L comprising an amplifier 1100 and a low pass filter 1200A formed by a resistor 1210 and the capacitive load L itself.

[0008] In this configuration, the current drawn from amplifier 1100 can be limited at high frequencies, thanks to the low pass filter 1200A. This configuration is however not efficient since the amplifier 1100 is set to output the maximum voltage and/or a significant portion of the output power is dissipated by the series resistor 1210.

[0009] Another known solution is illustrated in figure 1B, which schematically illustrates a circuit 1000B for driving a capacitive load L. Here the low pass filter 1200B is positioned before the amplifier 1100, in order to avoid the high power dissipation in the series transistor 1210.

[0010] Also in this case, however, the low-pass filter 1200B must be designed for the worst-case scenario. This includes the maximum load capacitance, the maximum input signal amplitude and the maximum frequency. On a battery-operated device, this further includes the lowest battery level. It is evident that such worst-case scenario is not a frequent situation so that, for most of the operating time, the filter 1200B results in an excessive filtering. For instance, in the case of a piezoelectric component used for generating sound, as the capacitive load L, this implementation lowers the available sound to pressure level of the transducer under conditions where this would not normally be needed.

[0011] Figure 1C illustrates a yet another alternative driving circuit 1000C comprising an adaptive filter 1300 and a model 1400 of the load. The adaptive filter 1300 can control voltage and/or current between the input signal and the amplifier 1100 based on the model 1400 of the load L. This can overcome the worst-case filter design limitation, discussed for figure 1B, by updating the model in accordance with the specific characteristics of the load, for instance during an initial characterization phase.

[0012] This implementation is nevertheless also not ideal, since the load model 1400 is fixed and does not track the load variations. This forces the load model to be based on a worst-case assumption. Moreover, for battery-operated devices, there is no information about the system battery level, so that design assumptions concerning the available current and/or voltage from the battery also have to be made for the worst-case conditions.

[0013] There is therefore a need to provide a driving circuit and/or method which allows an efficient driving of a capacitive load, particularly for implementations in battery-operated devices.

[0014] Driving circuits according to the prior art are known, for instance, from US 2019/260333 A1.

Summary

[0015] In general, the invention relies on an adaptive filter, whose characteristics are dynamically adjusted. The adjustment can be in particular based on dynamically adjusted characteristics of the load and of the battery. Thanks to the dynamic adjustment of the filter it is possible to maximize the driving signals to the load without introducing artefacts

or triggering over current protection mechanisms. In particular, the invention is defined by independent claim 1.

[0016] An embodiment useful for understanding the invention can relate to a circuit for driving a capacitive load comprising: an amplifier for driving the load based on an input signal, the amplifier comprising at least a boost converter, a dynamic model configured to track a capacitance of the load and a voltage of the source for powering at least parts of the circuit, an adaptive filter, configured to filter the input signal based on an output of the dynamic model.

[0017] Thanks to this configuration it is advantageously possible to drive the capacitive load by taking into account variations in the capacitance value of the load as well as in the voltage of the power source. This allows the adaptive filter to be operated under conditions representative of the actual driving configuration instead of worst-case scenario configurations, which might otherwise needlessly limit the driving capability.

[0018] In some embodiments, the dynamic model can comprise a load current model configured to output a calculated amplifier current, the calculated amplifier current being a current expected to be outputted by the amplifier as a function of at least the input signal and of the tracked capacitance of the load, and/or a boost current model configured to output a calculated boost current, the calculated boost current being a current expected to be outputted by an inductor of the boost converter as a function of at least the input signal and the voltage of the source.

[0019] Thanks to this configuration it is advantageously possible to model those values based on easily available input signals. The modelled values can allow the dynamic model to drive the adaptive filter as function of the input signals as well as of the load and power supply conditions.

[0020] In some embodiments, the load current model can be configured to receive as input V_L a value representative of the voltage across the load, receive as input I_L a value representative of the current across the load, receive as input V_{IN} a value representative of the input signal, and output the calculated amplifier current I_{OUT_PRED} as $I_{OUT\_PRED} = f(V_{IN} * Y_L)$ where Y_L is the admittance of the load and where f is a bijective function.

[0021] Thanks to this configuration it is advantageously possible to compute the calculated amplifier current I_{OUT_PRED} in a simple and reliable manner.

[0022] In some embodiments, the load current model can comprise a load capacitance model configured to output a calculated capacitance value of the load calculated from V_L and I_L, an amplifier model configured to output an expected output voltage of the amplifier calculated from V_{IN}, a current calculator configured to calculate the calculated amplifier current based on the calculated capacitance value of the load and on the expected output voltage as $I_{OUT\_PRED} = f(V_{OUT\_PRED} * Y_L)$ where f is a bijective function.

[0023] Thanks to this configuration it is advantageously possible to compute the calculated amplifier current I_{OUT_PRED} in a simple and reliable manner.

[0024] In some embodiments, the load capacitance model can comprise a least mean square filter.

[0025] Thanks to this configuration it is advantageously possible to simply and reliably compute the load capacitance based on voltage and current measurements of the signals across the load capacitance.

[0026] In some embodiments, the load current model can comprise a model of a voltage to current transfer function of the load.

[0027] Thanks to this configuration it is advantageously possible to simply and reliably compute the value of I_{OUT_PRED} by inserting the value of V_{OUT_PRED} into the transfer function, having C_L as variable

[0028] In some embodiments, the boost current model can be configured to receive as input V_{BAT} a value representative of the voltage across the source, receive as input η a value representative of an efficiency of the boost converter, receive as input I_{OUT_PRED} a value representative of the calculated amplifier current, receive as input V_{IN} a value representative of the input signal, output the calculated boost current I_{BST_PRED} as $I_{BST\_PRED} = f[V_{OUT} * I_{OUT\_PRED} / (\eta * V_{BAT})]$ where f is a bijective function.

[0029] Thanks to this configuration it is advantageously possible to compute the calculated boost current I_{BST_PRED} in a simple and reliable manner.

[0030] In some embodiments, the boost current model can comprise an amplifier model configured to output an expected output voltage of the amplifier calculated from V_{IN}, a current calculator configured to calculate the calculated boost current based on the expected output voltage.

[0031] Thanks to this configuration it is advantageously possible to compute the calculated boost current in a simple and reliable manner.

[0032] In some embodiments, the dynamic model can further comprise a coefficient computing logic configured to receive as input the calculated amplifier current and/or the calculated boost current, output at least one coefficient for controlling the adaptive filter based on values of at least one of the calculated amplifier current and the calculated boost current.

[0033] Thanks to this configuration it is advantageously possible to control the adaptive filter based on the calculated currents, which are a function of the actual driving conditions and not as a function of worst-case considerations.

[0034] In some embodiments, the adaptive filter can comprises a variable low-pass filter having as controlling input at least a roll-off coefficient, and the computing logic can be configured to compute the roll-off coefficient as a function of the

calculated boost current and/or of the calculated output current.

[0035]   Thanks to this configuration it is advantageously possible to control the roll-off coefficient of the adaptive filter based on the calculated currents, representing the actual driving conditions.

[0036]   In some embodiments, the coefficient computing logic can comprise a first peak detector configured to receive as input the calculated amplifier current and determine a maximum calculated amplifier current as a maximum value of the calculated amplifier current, and/or the coefficient computing logic can comprise a second peak detector configured to receive as input the calculated boost current and determine a maximum calculated boost current as a maximum value of the calculated boost current, wherein the coefficient computing logic can comprise a comparator configured to compare the maximum calculated amplifier current with a predetermined maximum amplifier current, and/or compare the maximum calculated boost current with a predetermined maximum boost current, output at least one coefficient based on a result of the comparison.

[0037]   Thanks to this configuration it is advantageously possible to control the values of the coefficients based on the maximum values reached by the currents, so that the adaptive filter can be controlled based on those maximum values, as those are the values which can cause the most artefacts.

[0038]   In some embodiments, the adaptive filter can comprise a multiplier having as controlling input at least a multiplier coefficient, and the computing logic can be configured to compute the multiplier coefficient as a function of the calculated boost current and/or of the calculated output current.

[0039]   Thanks to this configuration it is advantageously possible to provide more flexibility in how the adaptive filter operates on the input signal.

[0040]   In some embodiments, the coefficient computing logic can comprise at least one smoothing filter configured to receive as input the at least one coefficient, and the dynamic model can be configured to output the at least one coefficient after application of the least one smoothing filter.

[0041]   Thanks to this configuration it is advantageously possible to avoid fast variations of the filters which might cause artefacts in the amplification.

[0042]   In some embodiments, the circuit can further comprise a delay element connected between the input signal and the adaptive filter.

[0043]   Thanks to this configuration it is advantageously possible to allow sufficient time for the processing of the dynamic model.

[0044]   In some embodiments, the circuit can further comprise a second adaptive filter connected between the input signal and the dynamic model, wherein the second adaptive filter can be configured to provide substantially the same filtering of the adaptive filter, wherein the second adaptive filter is configured to filter the input signal based on the output of the dynamic model.

[0045]   Thanks to this configuration it is advantageously possible to provide an input to the dynamic model which is representative of the input provided to the amplifier.

[0046]   In some embodiments, the adaptive filter can comprise a plurality of low-pass filters and high-pass filters for filtering the input signal along at least two branches, preferably three.

[0047]   Thanks to this configuration it is advantageously possible to allow an easy control of the roll-off of the filter by use of coefficients applied to one or more of the branches.

[0048]   In some embodiments, the capacitive load can be a speaker based on one or more a piezoelectric components or MEMS.

[0049]   Thanks to this configuration it is advantageously possible to use the driving circuit for driving the speaker without introducing artefacts and without needlessly limiting the driving power applied to the speaker based on worst-case scenario considerations.

[0050]   A further embodiment of the invention can relate to a device comprising a speaker and a circuit according to any previous embodiment for driving the speaker.

[0051]   A further embodiment of the invention can relate to a computing unit comprising a processor and a memory, the memory comprising instructions which, when executed by the processor, cause the processor to operate as the circuit of any of the previous embodiments.

Brief description of the drawings

[0052]

Figures 1A-1C schematically illustrate driving circuits 1000A-1000C for a capacitive load L in accordance with the prior art;

Figure 2 schematically illustrates a driving circuit 2000;

Figure 3 schematically illustrates a driving circuit 3000 and figure 3A schematically illustrates an amplifier 3100, comprising a boost converter;

Figures 4A and 4C schematically illustrates possible components of a load current model 4410 while figure 4B schematically illustrates a possible modelling of a load L;

Figures 5A and 5B schematically illustrates possible components of a boost current model 5420;

Figure 6 schematically illustrates possible components of a filter 6300;

Figure 7 schematically illustrates possible components of a coefficient computing logic 7430;

Figure 8 schematically illustrates a driving circuit 8000;

Figure 9 schematically illustrates possible components of a filter 9300;

Figure 10 schematically illustrates a driving method 10000;

Figure 11 schematically illustrates a computing device 11000.

Detailed description of the drawings

[0053]   Some examples of the present disclosure generally provide for a plurality of circuits or other electrical devices. All references to the circuits and other electrical devices and the functionality provided by each are not intended to be limited to encompassing only what is illustrated and described herein. While particular labels may be assigned to the various circuits or other electrical devices disclosed, such labels are not intended to limit the scope of operation for the circuits and the other electrical devices. Such circuits and other electrical devices may be combined with each other and/or separated in any manner based on the particular type of electrical implementation that is desired.

[0054]   It is recognized that any circuit or other electrical device disclosed herein may include any number of micro-controllers, a graphics processor unit (GPU), integrated circuits, memory devices (e.g., FLASH, random access memory (RAM), read only memory (ROM), electrically programmable read only memory (EPROM), electrically erasable pro-grammable read only memory (EEPROM), or other suitable variants thereof), and software which co-act with one another to perform operation(s) disclosed herein. In addition, any one or more of the electrical devices may be configured to execute a program code that is embodied in a non-transitory computer readable medium programmed to perform any number of the functions as disclosed.

[0055]   In the following, embodiments of the invention will be described in detail with reference to the accompanying drawings. It is to be understood that the following description of embodiments is not to be taken in a limiting sense. The scope of the invention is not intended to be limited by the embodiments described hereinafter or by the drawings, which are taken to be illustrative only.

[0056]   The drawings are to be regarded as being schematic representations and elements illustrated in the drawings are not necessarily shown to scale. Rather, the various elements are represented such that their function and general purpose become apparent to a person skilled in the art. Any connection or coupling between functional blocks, devices, components, or other physical or functional units shown in the drawings or described herein may also be implemented by an indirect connection or coupling. A coupling between components may also be established over a wireless connection. Functional blocks may be implemented in hardware, firmware, software, or a combination thereof.

[0057]   According to the techniques described herein, it is possible to drive a capacitive load in a highly efficient manner, avoiding the triggering of over-voltage or over-current protections which would otherwise introduce artefacts in the driving signal as well as limiting energy consumption.

[0058]   Figure 2 schematically illustrates a driving circuit 2000 for a capacitive load L. In the context of the application, unless specified otherwise, the capacitive load can be any of a MEMS load, a piezoelectric component, a capacitor, or any other component which, when driven by a driving circuit, can be - as first approximation - modelled by one or more capacitors. Preferably, the capacitive load is a speaker, even more preferably a speaker implemented by a piezoelectric component.

[0059]   As visible in figure 2, the circuit 2000 comprises an amplifier 1100 for driving the load L based on an input signal V_{IN}. In particular, the amplifier 1100 comprises at least a boost converter so as to increase the voltage from a lower level V_{IN_FILT} to a higher lever V_L. In this manner it is possible to drive loads L which require higher driving voltages.

[0060]   The circuit 2000 further comprises a dynamic model 2400 configured to track a capacitance C_L of the load L and a voltage V_{BAT} of the source, for instance a battery, for powering at least parts of the circuit 2000. In particular, the source is

configured for powering at least the amplifier 1100. In preferred embodiments, the source can be configured for powering the entire circuit 2000.

[0061] While in this embodiment and throughout the remaining description reference is made to a battery, as energy source for driving the circuit 2000, it will be clear that similar considerations can apply to any other source, for instance any kind of voltage generator. The invention is particularly advantageous when applied to battery operated devices, as the voltage of the battery might change more than that of other sources, such as an AC powered voltage generator. However, the invention is not limited thereto.

[0062] The tracking of the voltage V_{BAT} can be achieved in known manners, for instance through a voltage sensor. It is noted that, for operating, the invention does not need the voltage V_{BAT} to correspond, in terms of Volts, to the tracked source voltage. It is sufficient that the voltage V_{BAT} provides an indication of the tracked source voltage. That is, the voltage V_{BAT} can result from any bi-univocal function applied to the tracked source voltage.

[0063] The tracking of the capacitance C_L can be also performed in known manners, for instance by measuring voltage V_L and current I_L and then computing capacitance C_L therefrom.

[0064] Additionally the circuit 2000 further comprises an adaptive filter 2300, configured to filter the input signal V_{IN} based on an output of the dynamic model 2400. Preferably, the adaptive filter 2300 can implement at least a low-pass filter having a predetermined cut-off frequency and roll-off value.

[0065] In general, in some embodiments, the dynamic model 2400 can provide an output to the adaptive filter 2300 which causes the adaptive filter 2300 to increase filtering when the voltage V_{BAT} is reduced. Alternatively, or in addition, the dynamic model 2400 can provide an output to the adaptive filter 2300 which causes the adaptive filter 2300 to increase filtering when the capacitance C_L is increased. Here, the increase of the filtering can be understood as to mean applying a lower cut-off frequency, and/or a higher roll-off value.

[0066] By tracking the capacitance of the load C_L and the voltage of the source V_{BAT}, the model 2400 can advantageously consider both parameters and avoid being designed for worst-case conditions or one or both of those parameters. This, in turn, allows the increase of the filtering to be limited to the conditions in which this is actually needed, thus avoiding excessive filtering which can lower the performances of the circuit 2000.

[0067] It is thus evident that several possible embodiments can be implemented so as to achieve the behaviour described above for the adaptive filter 2300 and its influence on the dynamic model 2400. In the following, some possible implementations will be described, the invention is however not limited thereto.

[0068] Figure 3 illustrates a circuit 3000 which differs from circuit 2000 due to the additional presence of blocks 3410, 3420 and 3430 in the dynamic model 3400, which might provide one example of an implementation of the dynamic model 2400. Although the illustrated embodiments operates with both blocks 3410 and 3420, it will be clear that, in some embodiments, only one of them might be implemented.

[0069] In particular, the dynamic model 3400 comprises a load current model 3410 configured to output a calculated amplifier current I_{OUT_PRED}, the calculated amplifier current I_{OUT_PRED} being a current expected to be outputted by the amplifier 1100 as a function of at least the input signal V_{IN} and of the tracked capacitance of the load C_L

[0070] Alternatively, or in addition, the dynamic model 3400 comprises a boost current model 3420 configured to output a calculated boost current I_{BST_PRED}, the calculated boost current I_{BST_PRED} being a current expected to be outputted by an inductor of the boost converter as a function of at least the input signal V_{IN} and the voltage of the source V_{BAT}.

[0071] To clarify the meaning of those currents, figure 3A schematically illustrates an amplifier 3100, comprising a boost converter 3110 and a driver 3120, powered by the boost converter 3110. It will be clear to those skilled in the art that several alternative potential implementations are however possible.

[0072] The calculated amplifier current I_{OUT_PRED} can be understood as being a computed version of the current I_{OUT} to be outputted by the amplifier 3100, and in particular by the driver 3120, as a function of a number of input parameters, including the input signal V_{IN} and the capacitance of the load C_L. Similarly, the calculated boost current I_{BST_PRED} can be understood as being a computed version of the current I_{BST} expected to cross the inductor in the boost converter 3110, as a function of a number of input parameters, including the input signal V_{IN} and the voltage of the source V_{BAT}.

[0073] The use of the indicated input parameters, for the respective current, allows a computation of the current which is both simple and reliable enough for further processing. Moreover the computation of the calculated amplifier current I_{OUT_PRED}, and/or of the calculated boost current I_{BST_PRED}, advantageously allows to provide a dynamic model 3400 which can be used to more finely control the adaptive filter 2300 than with other parameters.

[0074] It will be clear that the specific relationship between the calculated values and the respective input parameters can be depending on the specific topology of the amplifier, so that the skilled person will know how to compute the indicated values once the topology of the amplifier is defined.

[0075] In some embodiments, the function relating the calculated amplifier current I_{OUT_PRED} and the input signal V_{IN} can be such that I_{OUT_PRED} increases as V_{IN} increases, and/or I_{OUT_PRED} decreases as V_{IN} decreases. Alternatively, or in addition, the function relating the calculated amplifier current I_{OUT_PRED} and the capacitance C_L can be such that I_{OUT_PRED} increases as C_L increases, and/or I_{OUT_PRED} decreases as C_L decreases.

[0076] Similarly, in some embodiments, the function relating the calculated boost current I_{BST_PRED} and the input signal

V_{IN} can be such that I_{BST_PRED} increases as V_{IN} increases, and/or I_{BST_PRED} decreases as V_{IN} decreases. Alternatively, or in addition, the function relating the calculated boost current I_{BST_PRED} and the source voltage V_{BAT} can be such that I_{BST_PRED} increases as V_{BAT} decreases, and/or I_{BST_PRED} decreases as V_{BAT} increases.

[0077] Figure 4A schematically illustrates a load current model 4410, which can be a possible implementation of the load current model 3410. The load current model 4410 is configured to receive inputs V_L and I_L respectively representative of the voltage and current values across the load L or, as will be described more in details in the following, across a capacitance value of the load L.

[0078] Here, the term "a value representative of" is intended to indicate that the values inputted to the load current model 4410 allow the load current model 4410 to determine the respective value across the load. For instance, the input V_L can be, simply, the voltage V_L measured across the load. In other words, the term "a value representative of" can be interpreted, in its most direct implementation, as corresponding to the respective value.

[0079] However, the invention is not limited thereto and any value for V_L received by the load current model 4410, which allows the load current model 4410 to determine the voltage V_L measured across the load, can be used instead. For instance, the value V_L received by the load current model 4410 can be the voltage V_L measured across the load multiplied by a coefficient. Alternatively, or in addition, the value V_L received by the load current model 4410 can be a digital representation of the analog voltage V_L measured across the load. Still alternatively, or in addition, the value V_L received by the load current model 4410 can be a current value which is a function of the voltage value V_L measured across the load. Similar considerations apply to the input I_L.

[0080] The load current model 4410 is further configured to receive as input V_{IN} a value representative of the input signal V_{IN}. The same considerations above apply, for how input V_{IN} to the load current model 4410 can be a value representative of the input signal V_{IN}.

[0081] The load current model 4410 is then configured to output a calculated amplifier current I_{OUT_PRED} as

$$(Eq.\ 1)\ I_{OUT\_PRED} = f\ (V_{IN} * k * Y_L)$$

where Y_L is the admittance of the load L, k is a multiplication factor, preferably corresponding to the multiplication of amplifier 1100, and where f is a bijective function. In some implementations, the function f can simply be the identity function, that is, f can be removed from the equation above.

[0082] It is therefore clear how the calculated amplifier current I_{OUT_PRED} can be easily and reliably be calculated based on the input parameters. In particular, it will be clear to those skilled in the art how the admittance Y_L of the load L can be derived from the remaining input parameters, namely inputs V_L and I_L.

[0083] In some embodiments, the load L for the purpose of the computation of the admittance Y_L can be derived from the capacitance C of the load L alone. Alternatively, or in addition, the load L can be modelled to comprise the capacitance C, in series with one or more of an inductance L1, an inductance L2 and a resistor R1.

[0084] More specifically, as visible in figure 4B, the load L as seen by the amplifier 1100 can be modelled by a series connection of, in order, one or more of L_1, R_1, C_L and L_2. Although all of L_1, R_1, C_L and L_2 are illustrated in figure 4B it will be clear that the invention is not limited to this specific model, as the skilled person is aware of alternative manners for modelling the load L. In some embodiments, the inputs V_L and I_L can be understood to relate to measurements taken across the capacitance C_L and thus be used to derive the value of this capacitance in a known manner. The remaining parameters of the model, for instance L_1, R_1 and L_2, can be set to predetermined values, based on the known configuration of the load L.

[0085] Figure 4C schematically illustrates further details on how the load current model 4410 can be implemented, in some embodiments. In particular, in the illustrated implementation, the load current model 4410 can comprise a load capacitance model 4411 configured to output a calculated capacitance value C_{L_PRED} of the load L calculated from V_L and I_L. As discussed above, the computation of a capacitance value from the voltage and currents measures across the capacitance is known to the skilled person.

[0086] The load current model 4410 can further comprise an amplifier model 4412 configured to output an expected output voltage V_{OUT_PRED} of the amplifier calculated from V_{IN}. That is, the amplifier model 4412 can model the operation of the amplifier 1100. In this manner it is possible to compute the output V_{OUT_PRED} that the amplifier 1100 presents, when provided with an input V_{IN}. The amplifier model 4412 can be a simple gain stage or a more complex transfer function. In some embodiments, the amplifier model 4412 could depend on the signal frequency. In its simplest form, V_{OUT_PRED} can be obtained by V_{IN} by multiplying V_{OUT_PRED} by a multiplication factor applied by the amplifier 1100. The load current model 4410 can further comprise a current calculator 4413 configured to calculate the calculated amplifier current I_{OUT_PRED} based on the calculated capacitance value C_{L_PRED} of the load L and on the expected output voltage V_{OUT_PRED} as

$$(Eq.\ 2)\ I_{OUT\_PRED} = f\ (V_{OUT\_PRED} * Y_L)$$

where f is a bijective function. In some implementations, the function f can simply be the identity function, that is, f can be removed from the equation above.

[0087] Also in this case, the previous considerations made on Y_L apply. That is, the load L might be modelled by a circuit comprising more than the capacitance C_L computed by the load capacitance model 4411, and the computation of the resulting admittance Y_L, at the current calculator 4413, can take that into account, in known manners. In other words, the load current model 4410 allows tracking of a variable component C_L of the load. Any other components of the load L can be assigned to a predetermined value, based on the design of the load L.

[0088] As indicated above, the skilled person is aware of several manners for computing the value of C_L based on the inputs V_L and I_L. In a possible specific implementation, the load capacitance model 4411 can comprise a least mean square filter.

[0089] In particular, the load capacitance admittance can be defined as a function of C_L, for instance as $s* C_L$, and it can be represented in a discrete way as $\frac{az-b}{z+1}$ in a known manner.

[0090] The least mean square filter algorithm can be used to calculate the coefficients a and b, in a known manner, and thus the value of C_L.

[0091] Moreover, in some embodiments, the load current model 4410 can comprises a model of a voltage to current transfer function of the load L, and/or of the capacitance value C_L of the load L. In this manner, the value of I_{OUT_PRED} can be simply computed by inserting the value of V_{OUT_PRED} into the transfer function, having C_L as variable.

[0092] Several manners have thus been described for the computation of a predicted value I_{OUT_PRED} of the current I_{OUT}, that is, of the current that would be outputted by the amplifier 1100 as a function of a given load L, in particular of a given capacitance C_L of the load L, and as function of a given input signal V_{IN}.

[0093] This enables the dynamic model to compute what current I_{OUT_PRED} would be outputted by the amplifier 1100, should this current be available. As will become clearer in the following, this current can be compared to threshold values so that if the I_{OUT_PRED} cannot be achieved, the dynamic model can provide an indication to the adaptive filter 2300, in order to act on the signal V_{IN} so as to bring the current I_{OUT} to a value which can be sustained.

[0094] Moreover, as the computation of the current I_{OUT_PRED} is a function of the status of the load L, in particular of the status of a variable capacitance component C_L of the load L, the model can track, potentially and preferably in real time, the actual status of the load L instead of being pre-programmed to take into account the worst case scenario, in which the load L is drawing as much current as allowed by the design.

[0095] This is a significant advantage since, as it is known to those skilled in the art, semiconductor components can have characteristics with rather large ranges when evaluated under all possible conditions, such as process, age, temperature and driving conditions. However, the worst case scenario, namely the worst possible combination of those characteristics, is an event which is statistically very unlikely to happen, so that designing the model 2400 on a static set of parameters leads to severe filtering by filter 2300 which, in most cases, is not needed.

[0096] The description above provided details on how the calculated amplifier current I_{OUT_PRED} can be computed. In the following, it will be described how the calculated boost current I_{BST_PRED} can be computed. Considerations made above for the modelling of the load L continue to apply.

[0097] Figure 5A schematically illustrates a boost current model 5420, which can be a possible implementation of the boost current model 3420. The boost current model 5420 is configured to receive as inputs:

- V_{BAT}, a value representative of the voltage across the source,

- η, a value representative of an efficiency of the boost converter 3110,

- I_{OUT_PRED}, a value representative of the calculated amplifier current,

- V_{IN}, a value representative of the input signal,

output the calculated boost current I_{BST_PRED} as

$$I_{BST\_PRED} = f [V_{OUT} * I_{OUT\_PRED} / (\eta * V_{BAT})]$$

where V_{OUT} can be computed from V_{IN} in a known manner, for instance by the multiplication of V_{IN} and the amplification factor of the amplifier 1100, and where f is a bijective function. In some implementations, the function f can simply be the identity function, that is, f can be removed from the equation above.

[0098] This allows the calculated boost current I_{BST_PRED} to be easily and reliably computed. The value of the calculated

boost current I_{BST_PRED} provides an important indication on the current which is drawn from the power supply source, and, as will become clearer in the following, can be used to determine if this value is higher than what the power supply source can provide, which indicates that filtering is needed.

[0099] Moreover, by re-using the calculated amplifier current I_{OUT_PRED}, the dynamic model 3400 can make an efficient use of computational resources which have already been employed.

[0100] Figure 5B schematically illustrates further details on how the boost current model 5420 can be implemented, in some embodiments. In particular, in the illustrated implementation, the boost current model 5420 can comprise an amplifier model 4412 configured to output an expected output voltage V_{OUT_PRED} of the amplifier calculated from V_{IN}.

[0101] While the amplifier model 4412 is shown in figure 5B as being in addition to the one shown in figure 4C, it will be clear to those skilled in the art that the same amplifier model 4412 can be shared by the models 4410 and 5420. For instance, a single amplifier model could be connected to V_{IN}, so at to provide both blocks 3410 and 3420 with an expected output voltage V_{OUT_PRED}. Alternatively, or in addition, the model 4410 can output the value of V_{OUT_PRED} to the model 5420, in addition to the value of I_{OUT_PRED}.

[0102] The boost current model 5420 can further comprise a current calculator 5421 configured to compute the calculated boost current I_{BST_PRED} based on the expected output voltage V_{OUT_PRED} in a manner which will be clear to those skilled in the art.

[0103] In some embodiments, the current calculator 5421 can implement a function which provides an increase in the calculated boost current I_{BST_PRED} when the expected output voltage V_{OUT_PRED} increases, and/or a decrease in the calculated boost current I_{BST_PRED} when the expected output voltage V_{OUT_PRED} decreases. Alternatively, or in addition, the current calculator 5421 can implement a function which provides an increase in the calculated boost current I_{BST_PRED} when the source voltage V_{BAT} decreases, and/or a decrease in the calculated boost current I_{BST_PRED} when the source voltage V_{BAT} increases.

[0104] This provides an efficient manner for computing the calculated boost current I_{BST_PRED}.

[0105] It has thus been described how the calculated boost current I_{BST_PRED} and/or the calculated amplifier current I_{OUT_PRED} can be computed. As noted above, those values do not need to identically numerically represent the respective currents. That is, it is sufficient that the values of the calculated boost current I_{BST_PRED} and/or the calculated amplifier current I_{OUT_PRED} are linked in a known manner, through the bijective function f, to the respective currents.

[0106] As an example, if the amplifier current is corresponding to 10mA, for a given set of inputs, the calculated amplifier current I_{OUT_PRED} can be expressed, for instance if expressed as a voltage, as X Volts, as long as it is possible to associate the value 10mA to the value of X.

[0107] Based on the calculated boost current I_{BST_PRED} and/or the calculated amplifier current I_{OUT_PRED}, the dynamic model 3400 can provide one or more output to the adaptive filter 2300, which influence the operation of the adaptive filter 2300.

[0108] In general, if the value of any of the calculated boost current I_{BST_PRED} and/or the calculated amplifier current I_{OUT_PRED} is over a respective predetermined threshold, the dynamic model 3400 can provide one or more output to the adaptive filter 2300, which causes the adaptive filter 2300 to increase filtering of the input signal V_{IN}. More specific manners of operation implementing this general concept will be described more in details in the following.

[0109] As visible in figure 3 and 6, the dynamic model 3400 can further comprises a coefficient computing logic 3430 configured to receive as input the calculated amplifier current I_{OUT_PRED} and/or the calculated boost current I_{BST_PRED}, and output at least one value for controlling the adaptive filter 6300 based on values, preferably maximum values, of at least one of the calculated amplifier current I_{OUT_PRED} and the calculated boost current I_{BST_PRED}.

[0110] In particular, the adaptive filter 6300 can comprise a low-pass filter 6310, whose roll-off coefficient can be controlled by the value of R_{OFF}. For instance, as R_{OFF} increases, the roll-off coefficient can increase and as R_{OFF} decreases, the roll-off coefficient can decrease. Alternatively, or in addition, the adaptive filter 6300 can comprise a multiplier whose multiplication coefficient can be controlled by the value of X_{MULT}. For instance, as X_{MULT} increases, the multiplication coefficient can increase and as X_{MULT} decreases, the multiplication coefficient can decrease. **In** the following description, it is assumed that the adaptive filter 6300 implements both the control on R_{OFF} and on X_{MULT}. It will however be clear that embodiments are possible in which only one of those controls is possible.

[0111] In general, any of X_{MULT} and/or R_{OFF} can be calculated based on any of I_{OUT_PRED} and/or I_{BST_PRED}. In some preferred embodiments, any of any of X_{MULT} and/or R_{OFF} can be calculated based on both of I_{OUT_PRED} and/or I_{BST_PRED}.

[0112] In particular, the coefficient computing logic 3430 can be configured so that if at least one among I_{OUT_PRED} and/or I_{BST_PRED} is above a predetermined threshold, then at least one of X_{MULT} is reduced and/or R_{OFF} is increased. In other words, the coefficient computing logic 3430 can be configured so that if at least one among the currents is above a predetermined threshold, then the filtering of filter 6300 is increased, so that it can be ensured that the driving circuit can operate correctly, in particular without introducing artefacts due to saturation and/or limitation and/or protection circuits.

[0113] The thresholds for I_{OUT_PRED} and/or I_{BST_PRED} can thus be selected depending on the maximum respective current which can be sustained by the circuit and/or by the load and/or by the power supply. It will be clear to those skilled in the art how specific values of the threshold can be selected, depending on specific circuit configuration.

[0114] Thus, the coefficient computing logic 3430 can be configured to act on at least one of X_{MULT} and/or R_{OFF} if at least one among I_{OUT_PRED} and/or I_{BST_PRED} is above a predetermined threshold, so as to change the operation of filter 6300. While both X_{MULT} and/or R_{OFF} have the effect of reducing the amplitude of output signal V_{IN_FILT} compared to V_{IN}, it will be clear to those skilled in the art that their effect is different. In particular, X_{MULT} applies to all frequencies of the input signal while R_{OFF} applies only to frequencies above a certain cut-off frequency.

[0115] In preferred embodiments, the combined use of both X_{MULT} and R_{OFF} can thus be particularly advantageous. For instance, if a signal which is causing one of the calculated currents to pass its respective threshold is at a frequency lower than the cut-off frequency, increasing R_{OFF} will provide no effect. Similarly, if said signal is only slightly above the cut-off frequency, it would necessitate a strong increase of R_{OFF}, while a more moderate decrease of X_{MULT} might achieve the same result without limiting too much the other frequencies in the signal.

[0116] This can be achieved by advantageously configuring the computing logic 3430 to act on both X_{MULT} and R_{OFF} if at least one among I_{OUT_PRED} and/or I_{BST_PRED} is above a predetermined threshold. In preferred embodiments, where action is taken on both coefficients, it can be further preferred to configuring the computing logic 3430 so that, of the total filtering applied by filter 6300, more filtering is achieved by increasing R_{OFF} than by reducing X_{MULT}.

[0117] Alternatively, or in addition, the computing logic 3430 can be configured to act R_{OFF} at first and, if an increase of until a predetermined threshold does not suffice to bring the computed current, or the computed currents, below the respective threshold, then the computing logic 3430 can further act X_{MULT}, alone or in combination with R_{OFF}.

[0118] Although throughout the description embodiments are described with reference to the roll-off value of the filter 6310, in further alternative embodiments similar results can be obtained by acting on the cut-off frequency of the filter 6310, instead of, or in addition to, the action on the roll-off value. Thus, in the description, when reference is made to the increase of R_{OFF}, alternative embodiments can be implemented in which this can be replaced by, or added to, the decrease of the cut-off frequency. The same applies vice versa, for the decrease of R_{OFF}.

[0119] While above the general operation of the computing logic 3430 and of the filter 6300 have been provided, further specific possible implementations will be described in the following. It will be clear to those skilled in the art that the invention is not limited to those specific implementations.

[0120] In particular, in some embodiments, the adaptive filter 6300 can comprise the variable low-pass filter 6310 having as controlling input at least the roll-off coefficient R_{OFF}, and the computing logic 3430 can be configured to compute the roll-off coefficient R_{OFF} as a function of the calculated boost current I_{BST_PRED} and/or of the calculated output current I_{OUT_PRED}, preferably as previously described.

[0121] Moreover, in some embodiments, the adaptive filter 6300 can comprise the multiplier 6320 having as controlling input at least the multiplier coefficient X_{MULT}, and the computing logic 7430 can be configured to compute the multiplier coefficient X_{MULT} as a function of the calculated boost current I_{BST_PRED} and/or of the calculated output current I_{OUT_PRED}, preferably as previously described.

[0122] In some preferred embodiments, a smoothing filter, not illustrated, can be applied to the coefficient X_{MULT} and/or R_{OFF}. Preferably, the smoothing filter can have an attack time slow enough to avoid artefacts in the driving signal of the load L. In particular, if the load L is a piezoelectric speaker, the smoothing filter can be configured to have an attack time slow enough to avoid audible artefacts in the audio signal outputted by the speaker. That is, thanks to the presence of the smoothing filter it is possible to avoid an abrupt variation of the respective coefficient, which could generate artefacts. Specific values for the attack time will thus be depending on the specific configuration of the circuit and/or of the load. As a reference value, in some preferred embodiments, the attack time is preferably in the range of 1-100ms, even more preferably 50-500ms.

[0123] In the embodiments implementing the filter with a smoothing filter having an attack time higher than zero, if a local maximum occurs in the current prediction, the attack time might not react fast enough to prevent the overcurrent condition, which might then lead to artefacts due to possible current limitations. In those embodiments, the filtering based on the multiplier 6320 is thus particular advantageous, as it can react faster to the local overcurrent situation.

[0124] In preferred embodiments, the coefficient X_{MULT} can advantageously correspond to a ratio of a current threshold for I_{OUT_PRED} and/or I_{BST_PRED}, and the value of I_{OUT_PRED} and/or I_{BST_PRED} which has been detected as being over the respective threshold. As an example, if I_{OUT_PRED} is at 110% of the respective threshold, the coefficient X_{MULT} can advantageously correspond to 100/110, so that the multiplication by multiplier 6320 can bring the signal back to a level which does not result in an overcurrent situation.

[0125] In those embodiments operating based on both I_{OUT_PRED} and I_{BST_PRED}, if both current thresholds for I_{OUT_PRED} and I_{BST_PRED} are overcome by the respective currents, the coefficient X_{MULT} can preferably correspond to the lower of the two ratios computed as described above.

[0126] In further preferred embodiments, the operation of the multiplier 6320 can be advantageously limited to a time range corresponding to the attack time of the smoothing filter, so as to allow sufficient filtering also in this time region. Alternatively, the multiplier 6320 can be configured to provide a higher filtering in time range corresponding to the attack time of the filter than in the subsequent time range.

[0127] In the description above it has thus been exemplified how the filter 2300 can provide various kinds of filtering

based on the feedback received by the dynamic model 2400. In general, the operation of the dynamic model has been exemplified as being based on the computation of one or more currents and the comparison of those currents to predetermined thresholds, by the coefficient computing logic 3430, in order to output signals indicative of overcurrent situations. This comparison can be implemented by the coefficient computing logic 3430 in a plurality of manners which are per se known, for instance by implementing a comparator based on a differential amplifier, when operating with analog signals, or a digital comparator, when operating with digital signals.

[0128]   In the following, further specific embodiments will be described in which particularly advantageous implementations for the comparison are described, with reference to figure 7.

[0129]   In particular, as visible in figure 7, in some embodiments the coefficient computing logic 7430, which can be a possible further implementation of the coefficient computing logic 3430, can comprise a first peak detector 7431 and/or a second peak detector 7432.

[0130]   The first peak detector 7431 is configured to receive as input the calculated amplifier current I_{OUT_PRED} and determine a maximum calculated amplifier current $I_{OUT\_PRED\_MAX}$ as a maximum value of the calculated amplifier current I_{OUT_PRED}. Similarly, the second peak detector 7432 is configured to receive as input the calculated boost current I_{BST_PRED} and determine a maximum calculated boost current $I_{BST\_PRED\_MAX}$ as a maximum value of the calculated boost current I_{BST_PRED}.

[0131]   The coefficient computing logic 7430 can further comprises a comparator 7433 configured to compare the maximum calculated amplifier current $I_{OUT\_PRED\_MAX}$ with a predetermined maximum amplifier current I_{OUT_MAX}, and/or compare the maximum calculated boost current $I_{BST\_PRED\_MAX}$ with a predetermined maximum boost current I_{BST_MAX}, and output at least one coefficient R_{OFF}, X_{MULT} based on a result of the comparison.

[0132]   Concerning the specific changes to the one or more coefficient as a function of the one or more inputs, reference is made to the previously described embodiments. In particular, where previously reference has been made to a comparison of I_{OUT_PRED} and I_{BST_PRED} with the respective thresholds, similar considerations can apply to the comparison of $I_{OUT\_PRED\_PEAK}$ and $I_{BST\_PRED\_PEAK}$ with the respective thresholds, namely I_{OUT_MAX} and I_{BST_MAX}.

[0133]   The introduction of the peak detectors allow to consider the part of the current signals which lead to the overcurrent situations. This simplifies the input to the comparator 7433, which only has to operate on peak values and not on the complete signals. In some preferred embodiments, the peak detectors preferably output the maximum amplitude of their respective inputs. In some further preferred embodiments, they might also output information concerning the duration of the maximum amplitude, for instance in absolute and/or relative terms. This timing information can also be used by the comparator, by comparing it with respective timing thresholds, not illustrated. In this manner, if the timing information outputted by the peak detector is not higher than the respective threshold, the comparator can be configured to take no action of its outputs. This might be useful, for instance, to avoid reacting to very narrow peaks and/or spikes caused by noise, short transitory effects and/or measurement errors.

[0134]   As an alternative to this approach, and as visible in figure 7, the coefficient computing logic 7430 can comprises at least one smoothing filter 7434, 7435 configured to receive as input the at least one coefficient R_{OFF}, X_{MULT}, and to output the at least one coefficient R_{OFF}, X_{MULT} after application of the least one smoothing filter 7434, 7435.

[0135]   In this manner it can be abrupt changes in the transfer function of filter 2300 can be avoided. This avoid abrupt changes in the signal filtered by filter 2300, which could cause artefacts, for instance audible artefacts in case of using the circuit for driving a speaker as load. The optional smoothing filters thus provide a simple and effective way to low pass the output of the computing logic 743. In preferred embodiments, the one or more smoothing filter could be implemented by low-pass filters.

[0136]   It will further be clear that the implementation of the smoothing filter 7434 is independent from the implementation of the smoothing filter 7435. Moreover, those skilled in the art will appreciate that the characteristics of the smoothing filters 7434 and 7435 do not need to be the same. In particular, each of them can have its own attack and/or release time, which can be programmed to trade between avoiding audible artefacts and maximizing the algorithm effectiveness. In preferred embodiments, the attack and/or release time are preferably comprised between 10 microseconds and 1s, even more preferably between 100 microseconds and 500ms.

[0137]   It has thus been described how various embodiments of the invention can compute one or more currents of the driving circuit and how this information can be used as a feedback loop to filter the input signal, so as to avoid introducing artefacts in the signal due overcurrent situations.

[0138]   Figure 8 schematically illustrates a driving circuit 8000, which differs from the previously described embodiments due to, among others, the presence of a delay element 8500 connected between the input signal V_{IN} and the adaptive filter 2300.

[0139]   Generally, the purpose of the delay element is to allow the delay caused by the processing in the feedback loop, through the dynamic model 8400, to be compensated. in this manner it is possible to ensure that the part of the signal which is filtered by the filter 2300 is the one which was previously modelled by the dynamic model 8400.

[0140]   **In** some preferred embodiments, the delay introduced by delay element 8500 can therefore correspond to the processing time of the dynamic model 8400. Preferably, the processing time of the dynamic model 8400 can be understood

to be the time incurring between a change in one or more of its inputs and a corresponding change in one or more of its outputs.

[0141] **In** some practical implementations, it has been found that delays in between 0.5ms and 5ms offer a sufficient time for the processing of the dynamic model 8400 while not significantly negatively impacting the operation of the driving circuit.

[0142] Moreover, as visible in figure 8, the driving circuit 8000 differs from the previously described embodiments due to, among others, the presence of a second adaptive filter 8440 connected between the input signal V_{IN} and the dynamic model 8400.

[0143] It will be clear that the filter 8440 can be implemented independently of the delay 8500. In this respect, it is noted that throughout the description, various embodiments are illustrated and/or described, each comprising a plurality of features. This is not to be limiting the invention to the specific combination of features of the embodiments as illustrated and/or described. To the contrary, any feature from any of the embodiments can be combined with any features from any remaining embodiment.

[0144] In particular, the second adaptive filter 8440 can be configured to provide substantially the same filtering of the adaptive filter 2300. Here, the term substantially can be interpreted so as to mean that the filtering provided by the second adaptive filter 8440 is such that the signal outputted to the model 8400 allows the model 8400 to operate so that, when the model 8400 drives the filter 2300, it is possible to obtain the previously described operation, and in particular to avoid overcurrent situations in the driver 1100 and/or in the load L. In other words, while the filters 2300 and 8440 do not need to provide exactly the same output, they will provide an output similar enough for allowing the operation of the model 8400 in accordance with its purpose, as previously defined.

[0145] In further embodiments, the second adaptive filter 8440 can be configured to provide a filtering within a range of +/- 10% of the filtering applied by the adaptive filter 2300. In further embodiments, the second adaptive filter 8440 can be configured to provide the same filtering of filter 2300.

[0146] Moreover, the second adaptive filter 8440 can be configured to filter the input signal V_{IN} based on the output of the dynamic model, in a manner similar to what has been discussed with respect to filter 2300. This ensures that the output of filter 8440 is compatible with that of filter 2300, so that the model 8400 can more precisely model the evolution of the currents in the circuit.

[0147] Figure 9 illustrates a further possible implementation of filter 2300, in form of adaptive filter 9300. As visible in figure 9, the adaptive filter 9300 can comprise a plurality of low-pass filters and high-pass filters for filtering the signal V_{IN} along at least two branches, preferably three. For instance, a first branch comprises low-pass filter 9331, a second branch comprises high-pass filter 9332 and low-pass filter 9341, a third branch comprises high-pass filter 9332 and high-pass filter 9342.

[0148] The output V_{IN_FILT} of the filter 9300 is obtained by combining the output of at least two branches through an adder 9360.

[0149] Preferably, before the combination, the output of one or more branches can be multiplied by a gain. For instance, the output of the second branch as illustrated is multiplied by the gain G_1 at multiplier 9351, while the output of the third branch as illustrated is multiplied by the gain G_2 at multiplier 9352.

[0150] In preferred embodiments, the high-pass filter 9332 and the low-pass filter 9331 constitute an all-pass section 9330. Similarly, the high-pass filter 9342 and the low-pass filter 9341 can constitute an all-pass section 9340.

[0151] Such configuration is particularly advantageous. In particular, it allows an easy control of the roll-off of filter 9300. In particular, when no filtering action is required, that is a roll-off value of 0 dB/decade, the filter 9300 can implement an all-pass filter by appropriately controlling G_1 and G_2 and/or by appropriately controlling the cut-off frequency of all-pass section 9330 and/or of all-pass section 9340.

[0152] In particular, in some embodiments, an iterative process can be configured to identify the low pass and the high pass filter cut off frequencies and G_1 and G_2 so that the filter 9300 is an approximation of a requested profile.

[0153] More specifically, in some embodiments G_1 and G_2 can be determined as

$$G_1 = 10^{((dB \cdot delta_1)/20)}$$

$$G_2 = 10^{((dB \cdot delta_2)/20)}$$

[0154] Where dB is the desired roll off and where $delta_1$ and $delta_2$ can be determined by an iterative process as a function of the desired roll-off.

[0155] It has thus been described how the invention can provide a circuit for driving a generic capacitive load L. As it is evident from the description above, this applies to any capacitive load and has the advantage of being able to track possible variation in the capacitance and/or in the power supply when filtering the input signal, so as to avoid overcurrent situations

which might lead to the presence of artefacts in the signal.

[0156] Such behavior, while desirable when driving any load L, is particularly advantageous when the capacitive load L is a speaker, and even more preferably so when the speaker is based on one or more a piezoelectric components or MEMS. Various manners are known for implementing a speaker with those technologies and are per se known.

[0157] Further it is noted that the invention can obtain the advantages described above without measuring the load L directly, but relying on measurements of voltages and/or currents across the load L and/or at the output of the driver 1000. Thus the invention can be applied to a wide range of loads, without significant changes.

[0158] While the invention has been directed to a driving circuit, it will be clear that is can also be directed to a device, such as a mobile phone, a table, a notebook, or more generally any kind of electronic device comprising a speaker, preferably based on one or more a piezoelectric components or MEMS, and a circuit according to any of the described embodiments, for driving the speaker.

[0159] Additionally, while the invention has been described in terms of an apparatus, it is evident to those skilled in the art that a corresponding method and/or computing device can be implemented.

[0160] In general, all functionalities described with reference to the dynamic model and the adaptive filter above can be implemented by corresponding method steps and/or by corresponding instructions executed by a CPU.

[0161] For instance, figure 10 illustrates a method comprising steps S101-S104.

[0162] Step S101 comprises acquiring inputs for the dynamic models. The inputs can be any of the previously described inputs, such as, for instance, any of V_{IN}, V_L, I_L, V_{BAT}, η , and more generally any of the values which have been described as being inputted in the dynamic model. In preferred embodiments, the inputs tracked by the dynamic model comprise at least the capacitance C_L of the load L and the voltage V_{BAT} of the source used for powering at least parts of the circuit.

[0163] Step S102 comprises computing one or more outputs of the dynamic model. The outputs can be any of the previously described outputs, such as, for instance, any of X_{MULT}, R_{OFF}, G_1, G_2, η, and more generally any of the values which have been described as being outputted by the dynamic model.

[0164] Step S103 comprises configuring the filter based on the outputs of the dynamic model, as previously described, which might vary depending on the specific configuration of the filter.

[0165] Step S104 comprises filtering the input signal with the configured filter while driving the load L.

[0166] Further steps can be defined to carry out the functionalities previously described in terms of apparatus features.

[0167] Similarly, the invention can be implemented by a computing device 11000 in which the various functionalities previously described can be implemented by appropriately driving a processor. With reference to figure 11, the computing device 11000 can in particular comprise a processor 11000, input/output means 11200 and a memory 11300. The memory can comprise instructions which, when executed by the processor, can cause the processor to execute any of the functionalities previously described. Moreover, through input/output means 11200, possibly driven directly based on instructions from the memory and/or through the processor, it is possible to acquire the one or more inputs and provide the one or more outputs.

[0168] In particular, the invention could also be implemented as a combination of discrete components and a computing device. Preferably, the computing device could be used to implement the dynamic model and/or the various filters, while discrete components could be used for the remaining features, and notably for the driver.

[0169] It has therefore been shown how a capacitive load can be driven in an efficient way, taking into account real-world conditions and not based on worst-case assumptions. This allows the load to be driven without needlessly sacrificing driving power which is instead available and can be used without generating artefacts in the driving signal. At the same time, the configuration of the invention allows the amplification to be reduced in real-time for the conditions of load, power supply and driving signal which would otherwise lead to the generation of artefacts.

[0170] While several embodiments with various feature have been discussed and/or illustrated, it will be clear to those skilled in the art that the invention is not limited to those specific combinations of features. Instead, further embodiments can be obtained by combining features separately from one or more embodiments, within the scope of the claims.

List of reference numerals

[0171]

    1000A: driving circuit
    1100: amplifier
    1200A: low pass filter
    1210: resistance
    L: capacitive load
    1000B: driving circuit

1200B: low pass filter
1000C: driving circuit
1300: adaptive filter
1400: load model
2000: driving circuit
2300: adaptive filter
2400: dynamic model
V_{IN}: input signal
V_L: measured load voltage
I_L: measured load current
C_L: load capacitance
V_{BAT}: source voltage
3000: driving circuit
3100: amplifier
3110: boost converter
3120: driver
3400: dynamic model
3410: load current model
3420: boost current model
3430: coefficient computing logic
I_{OUT_PRED}: calculated amplifier current
I_{BST_PRED}: calculated boost current
4410: load current model
4411: load capacitance model
4412: amplifier model
4413: current calculator
C_{L_PRED}: calculated load capacitance
V_{OUT_PRED}: expected amplifier output voltage
5420: boost current model
5421: current calculator

η : boost converter efficiency
6300: adaptive filter
6310: low-pass filter
6320: multiplier
7430: coefficient computing logic
7431, 7432: peak detector
7433 comparator
7434, 7435: smoothing filter
8000: driving circuit
8400: dynamic model
8440: delay
8500: delay
9300: adaptive filter
9330: all-pass section
9331: low pass filter
9332: high pass filter
9340: all-pass section
9341: low pass filter
9342: high pass filter
9351, 9352: multiplier
9360: adder
10000: method
S101: acquiring inputs
S102: computing outputs
S103: configuring filter
S104: filtering signal
11000: computing unit

11100: processor
11200: Input/Output
11300: memory

Claims

1. A circuit (2000, 3000, 8000) for driving a capacitive load (L) comprising:

   an amplifier (1100, 3100) configured to drive the load (L) based on a filtered input signal (V_{IN_FILT}), the amplifier comprising at least a boost converter (3110) configured to power a driver (3120) based on a voltage of a source (VBAT), the driver (3120) being configured to receive the filtered input signal (V_{IN_FILT}) and drive the load (L), a dynamic model (2400, 3400, 8400) configured to track a capacitance of the load ($\overline{C}_L$) and configured to provide an output based on the capacitance of the load (C_L),
   an adaptive filter (2300, 6300, 9300), configured to filter an input signal (V_{IN}) based on the output of the dynamic model (2400, 3400, 8400), and output the filtered input signal (V_{IN_FILT}),
   wherein the boost converter is configured to increase a voltage of the filtered input signal (V_{IN_FILT}) from a lower level to a higher lever (V_L), for driving the load (L),
   wherein
   the dynamic model (2400, 3400, 8400) is further configured to track the voltage of the source (V_{BAT}) for powering at least parts of the circuit (2000, 3000, 8000) and further configured to provide the output based on the capacitance of the load (C_L) and the voltage of the source (V_{BAT}).

2. The circuit (3000, 8000) according to claim 1,
   wherein the dynamic model (3400, 8400) comprises

   a load current model (3410, 4410) configured to output a calculated amplifier current (I_{OUT_PRED}), the calculated amplifier current (I_{OUT_PRED}) being a current expected to be outputted by the amplifier (1100, 3100) as a function of at least the input signal (V_{IN}) and of the tracked capacitance of the load (C_L), and/or
   a boost current model (3420, 5420) configured to output a calculated boost current (I_{BST_PRED}), the calculated boost current (I_{BST_PRED}) being a current expected to be outputted by an inductor of the boost converter as a function of at least the input signal (V_{IN}) and the voltage of the source (V_{BAT}).

3. The circuit (3000, 8000) according to claim 2, wherein the load current model (4410) is configured to

   receive as input V_L a value representative of the voltage across the load (L),
   receive as input I_L a value representative of the current across the load (L),
   receive as input V_{IN} a value representative of the input signal, and
   output the calculated amplifier current I_{OUT_PRED} as

   $$I_{OUT\_PRED} = f\left(V_{IN} * Y_L\right)$$

   where Y_L is the admittance of the load (L) and where f is a bijective function.

4. The circuit (3000, 8000) according any of claims 2 or 3, wherein the load current model (4410) comprises

   a load capacitance model (4411) configured to output a calculated capacitance value (C_{L_PRED}) of the load (L) calculated from V_L and I_L,
   an amplifier model (4412) configured to output an expected output voltage (V_{OUT_PRED}) of the amplifier calculated from V_{IN},
   a current calculator (4413) configured to calculate the calculated amplifier current (I_{OUT_PRED}) based on the calculated capacitance value (C_{L_PRED}) of the load (L) and on the expected output voltage (V_{OUT_PRED}) as

   $$I_{OUT\_PRED} = f\left(V_{OUT\_PRED} * Y_L\right)$$

   where f is a bijective function.

5. The circuit (3000, 8000) according to claim 4, wherein the load capacitance model (4411) comprises a least mean square filter.

6. The circuit (3000, 8000) according to any of claims 3 to 5, wherein the load current model (4410) comprises a model of a voltage to current transfer function of the load (L).

7. The circuit (3000, 8000) according to any of claims 2 to 6, wherein the boost current model (5420) is configured to

   receive as input V_{BAT} a value representative of the voltage across the source,

   receive as input η a value representative of an efficiency of the boost converter,
   receive as input I_{OUT_PRED} a value representative of the calculated amplifier current,
   receive as input V_{IN} a value representative of the input signal,
   output the calculated boost current I_{BST_PRED} as

$$I_{BST\_PRED} = f\left[V_{OUT} * I_{OUT\_PRED} / (\eta * V_{BAT})\right]$$

   where f is a bijective function.

8. The circuit (3000, 8000) according to any of claims 2 to 7,
   wherein the dynamic model (3400, 8400) further comprises a coefficient computing logic (3430, 7430) configured to

   receive as input the calculated amplifier current (I_{OUT_PRED}) and/or the calculated boost current (I_{BST_PRED}),
   output at least one coefficient (R_{OFF}, X_{MULT}) for controlling the adaptive filter (2300, 6300, 9300) based on values of at least one of the calculated amplifier current (I_{OUT_PRED}) and the calculated boost current (I_{BST_PRED}).

9. The circuit (3000, 8000) according to claim 8, wherein

   the adaptive filter (6300, 9300) comprises a variable low-pass filter (6310) having as controlling input at least a roll-off coefficient (R_{OFF}), and
   the computing logic (3430, 7430) is configured to compute the roll-off coefficient (R_{OFF}) as a function of the calculated boost current (I_{BST_PRED}) and/or of the calculated output current (I_{OUT_PRED}).

10. The circuit (8000) according to any previous claim, further comprising a delay element (8500) connected between the input signal (V_{IN}) and the adaptive filter (2300, 6300, 9300).

11. The circuit (8000) according to any previous claim, further comprising a second adaptive filter (8440) connected between the input signal (V_{IN}) and the dynamic model (3400, 8400),

   wherein the second adaptive filter (8440) is configured to provide substantially the same filtering of the adaptive filter (2300, 6300, 9300),
   wherein the second adaptive filter (8440) is configured to filter the input signal (V_{IN}) based on the output of the dynamic model (3400, 8400).

12. The circuit (3000, 8000) according to any previous claim,
   wherein the adaptive filter (9300) comprises a plurality of low-pass filters (9331, 9341) and high-pass filters (9332, 9342) for filtering the input signal (V_{IN}) along at least two branches, preferably three.

13. The circuit (8000) according to any previous claim,
   wherein the capacitive load (L) is speaker based on one or more a piezoelectric components or MEMS.

14. A device comprising a speaker and a circuit (2000, 3000, 8000) according to any previous claim for driving the speaker.

15. A computing unit (10000) comprising a processor (10100) and a memory (10300), the memory comprising instructions which, when executed by the processor, cause the processor to operate as the circuit of any of claims 1-13.

Patentansprüche

1. Schaltung (2000, 3000, 8000) zum Ansteuern einer kapazitiven Last (L), umfassend:

   einen Verstärker (1100, 3100), der so konfiguriert ist, dass er die Last (L) auf der Grundlage eines gefilterten Eingangssignals (V_{IN_FILT}) ansteuert, wobei der Verstärker mindestens einen Boost-Konverter (3110) umfasst, der so konfiguriert ist, dass er einen Treiber (3120) auf der Grundlage einer Spannung einer Quelle (VBAT) versorgt, wobei der Treiber (3120) so konfiguriert ist, dass er das gefilterte Eingangssignal (V_{IN_FILT}) empfängt und die Last (L) ansteuert,
   ein dynamisches Modell (2400, 3400, 8400), das so konfiguriert ist, dass es eine Kapazität der Last (C_L) verfolgt, und das so konfiguriert ist, dass es eine Ausgabe auf der Grundlage der Kapazität der Last (C_L) bereitstellt,
   ein adaptives Filter (2300, 6300, 9300), das so konfiguriert ist, dass es ein Eingangssignal (V_{IN}) auf der Grundlage der Ausgabe des dynamischen Modells (2400, 3400, 8400) filtert und das gefilterte Eingangssignal (V_{IN_FILT}) ausgibt,
   wobei der Boost-Konverter so konfiguriert ist, dass er eine Spannung des gefilterten Eingangssignals (V_{IN_FILT}) von einem niedrigeren Pegel auf einen höheren Pegel (V_L) erhöht, um die Last (L) anzusteuern,
   wobei
   das dynamische Modell (2400, 3400, 8400) ferner so konfiguriert ist, dass es die Spannung der Quelle (V_{BAT}) verfolgt, um mindestens Teile der Schaltung (2000, 3000, 8000) mit Strom zu versorgen, und ferner so konfiguriert ist, dass es die Ausgabe auf der Grundlage der Kapazität der Last (C_L) und der Spannung der Quelle (V_{BAT}) bereitstellt.

2. Schaltung (3000, 8000) nach Anspruch 1,

   wobei das dynamische Modell (3400, 8400) Folgendes umfasst
   ein Laststrommodell (3410, 4410), das so konfiguriert ist, dass es einen berechneten Verstärkerstrom (I_{OUT_PRED}) ausgibt, wobei der berechnete Verstärkerstrom (I_{OUT_PRED}) ein Strom ist, von dem erwartet wird, dass er von dem Verstärker (1100, 3100) als eine Funktion von mindestens dem Eingangssignal (V_{IN}) und der nachgeführten Kapazität der Last (C_L) ausgegeben wird, und/oder
   ein Boost-Strommodell (3420, 5420), das so konfiguriert ist, dass es einen berechneten Boost-Strom (I_{BST_PRED}) ausgibt, wobei der berechnete Boost-Strom (I_{BST_PRED}) ein Strom ist, von dem erwartet wird, dass er von einer Induktionsspule des Boost-Konverters als eine Funktion von mindestens dem Eingangssignal (V_{IN}) und der Spannung der Quelle (V_{BAT}) ausgegeben wird.

3. Schaltung (3000, 8000) nach Anspruch 2, wobei das Laststrommodell (4410) so konfiguriert ist, dass es

   als Eingang V_L einen Wert empfängt, der für die Spannung über der Last (L) repräsentativ ist,
   als Eingang I_L einen Wert empfängt, der für den Strom über der Last (L) repräsentativ ist,
   als Eingang V_{IN} einen Wert empfängt, der für das Eingangssignal repräsentativ ist, und
   den berechneten Verstärkerstrom I_{OUT_PRED} als

   $$I_{OUT\_PRED} = f\left(V_{IN} * Y_L\right)$$

   ausgibt,
   wobei Y_L die Admittanz der Last (L) ist und wobei f eine bijektive Funktion ist.

4. Schaltung (3000, 8000) nach einem der Ansprüche 2 oder 3, wobei das Laststrommodell (4410) Folgendes umfasst

   ein Lastkapazitätsmodell (4411), das so konfiguriert ist, dass es einen berechneten Kapazitätswert (C_{L_PRED}) der Last (L) ausgibt, der aus V_L und I_L berechnet wird,
   ein Verstärkermodell (4412), das so konfiguriert ist, dass es eine erwartete Ausgangsspannung (V_{OUT_PRED}) des Verstärkers ausgibt, die aus V_{IN} berechnet wird, einen Stromrechner (4413), der so konfiguriert ist, dass er den berechneten Verstärkerstrom (I_{OUT_PRED}) auf der Grundlage des berechneten Kapazitätswertes (C_{L_PRED}) der Last (L) und der erwarteten Ausgangsspannung (V_{OUT_PRED}) wie folgt berechnet

   $$I_{OUT\_PRED} = f\left(V_{OUT\_PRED} * Y_L\right),$$

wobei f eine bijektive Funktion ist.

5. Schaltung (3000, 8000) nach Anspruch 4, wobei das Lastkapazitätsmodell (4411) ein Least-Mean-Square-Filter umfasst.

6. Schaltung (3000, 8000) nach einem der Ansprüche 3 bis 5, wobei das Laststrommodell (4410) ein Modell einer Spannungs-Strom-Übertragungsfunktion der Last (L) umfasst.

7. Schaltung (3000, 8000) nach einem der Ansprüche 2 bis 6, wobei das Boost-Strommodell (5420) so konfiguriert ist, dass es

als Eingang V_{BAT} einen Wert empfängt, der für die Spannung über der Quelle repräsentativ ist,
als Eingang η einen Wert empfängt, der für den Wirkungsgrad des Boost-Konverters repräsentativ ist,
als Eingang I_{OUT_PRED} einen Wert empfängt, der für den berechneten Verstärkerstrom repräsentativ ist,
als Eingang V_{IN} einen Wert empfängt, der für das Eingangssignal repräsentativ ist, den berechneten Boost-Strom I_{BST_PRED} als

$$I_{BST\_PRED} = f\left[V_{OUT} * I_{OUT\_PRED} / (\eta * V_{BAT})\right]$$

ausgibt,
wobei f eine bijektive Funktion ist.

8. Schaltung (3000, 8000) nach einem der Ansprüche 2 bis 7,

wobei das dynamische Modell (3400, 8400) ferner eine Koeffizientenberechnungslogik (3430, 7430) umfasst, die so konfiguriert ist, dass es als Eingang den berechneten Verstärkerstrom (I_{OUT_PRED}) und/oder den berechneten Boost-Strom (I_{BST_PRED}) empfängt,
mindestens einen Koeffizienten (R_{OFF}, X_{MULT}) zur Steuerung des adaptiven Filters (2300, 6300, 9300) auf der Grundlage von Werten von mindestens einem aus dem berechneten Verstärkerstrom (I_{OUT_PRED}) und/oder dem berechneten Boost-Strom (I_{BST_PRED}) ausgibt.

9. Schaltung (3000, 8000) nach Anspruch 8, wobei

das adaptive Filter (6300, 9300) ein variables Tiefpassfilter (6310) umfasst, das als Steuereingang mindestens einen Roll-Off-Koeffizienten (R_{OFF}) aufweist, und
die Berechnungslogik (3430, 7430) so konfiguriert ist, dass sie den Roll-Off-Koeffizienten (R_{OFF}) als Funktion des berechneten Boost-Stroms (I_{BST_PRED}) und/oder des berechneten Ausgangsstroms (I_{OUT_PRED}) berechnet.

10. Schaltung (8000) nach einem der vorstehenden Ansprüche, ferner umfassend ein Verzögerungselement (8500), das zwischen dem Eingangssignal (V_{IN}) und dem adaptiven Filter (2300, 6300, 9300) angeschlossen ist.

11. Schaltung (8000) nach einem der vorstehenden Ansprüche, ferner umfassend ein zweites adaptives Filter (8440), das zwischen dem Eingangssignal (V_{IN}) und dem dynamischen Modell (3400, 8400) angeschlossen ist,

wobei das zweite adaptive Filter (8440) so konfiguriert ist, dass es im Wesentlichen die gleiche Filterung wie das adaptive Filter (2300, 6300, 9300) bereitstellt,
wobei das zweite adaptive Filter (8440) so konfiguriert ist, dass es das Eingangssignal (V_{IN}) auf der Grundlage des Ausgangs des dynamischen Modells (3400, 8400) filtert.

12. Schaltung (3000, 8000) nach einem der vorstehenden Ansprüche,
wobei das adaptive Filter (9300) eine Vielzahl von Tiefpassfiltern (9331, 9341) und Hochpassfiltern (9332, 9342) zum Filtern des Eingangssignals (V_{IN}) entlang mindestens zweier, vorzugsweise dreier, Zweige umfasst.

13. Schaltung (8000) nach einem der vorstehenden Ansprüche,
wobei die kapazitive Last (L) auf einem oder mehreren piezoelektrischen Bauteilen oder MEMS lautsprecher-basiert ist.

14. Vorrichtung, umfassend einen Lautsprecher und eine Schaltung (2000, 3000, 8000) nach einem der vorstehenden Ansprüche zur Ansteuerung des Lautsprechers.

15. Recheneinheit (10000) mit einem Prozessor (10100) und einem Speicher (10300), wobei der Speicher Befehle umfasst, die, wenn sie vom Prozessor ausgeführt werden, den Prozessor veranlassen, wie die Schaltung nach einem der Ansprüche 1 bis 13 zu arbeiten.

Revendications

1. Circuit (2000, 3000, 8000) pour l'excitation d'une charge capacitive (L) comprenant :

un amplificateur (1100, 3100) configuré pour exciter la charge (L) sur la base d'un signal d'entrée filtré (V_{IN_FILT}), l'amplificateur comprenant au moins un convertisseur élévateur (3110) configuré pour alimenter en énergie un excitateur (3120) sur la base d'une tension d'une source (VBAT), l'excitateur (3120) étant configuré pour recevoir le signal d'entrée filtré (V_{IN_FILT}) et exciter la charge (L),
un modèle dynamique (2400, 3400, 8400) configuré pour surveiller une capacité de la charge (C_L) et configuré pour fournir une sortie sur la base de la capacité de la charge (C_L),
un filtre adaptatif (2300, 6300, 9300), configuré pour filtrer un signal d'entrée (V_{IN}) sur la base de la sortie du modèle dynamique (2400, 3400, 8400), et délivrer en sortie le signal d'entrée filtré (V_{IN_FILT}),
dans lequel le convertisseur élévateur est configuré pour augmenter une tension du signal d'entrée filtré (V_{IN_FILT}) d'un niveau inférieur à un niveau supérieur (V_L), pour l'excitation de la charge (L),
dans lequel
le modèle dynamique (2400, 3400, 8400) est en outre configuré pour surveiller la tension de la source (V_{BAT}) pour l'alimentation en énergie au moins de parties du circuit (2000, 3000, 8000) et en outre configuré pour fournir la sortie sur la base de la capacité de la charge (C_L) et de la tension de la source (V_{BAT}).

2. Circuit (3000, 8000) selon la revendication 1,

dans lequel le modèle dynamique (3400, 8400) comprend
un modèle de courant de charge (3410, 4410) configuré pour délivrer en sortie un courant d'amplificateur calculé (I_{OUT_PRED}), le courant d'amplificateur calculé (I_{OUT_PRED}) étant un courant prévu d'être délivré en sortie par l'amplificateur (1100, 3100) en fonction d'au moins le signal d'entrée (V_{IN}) et de la capacité surveillée de la charge (C_L), et/ou
un modèle de courant élévateur (3420, 5420) configuré pour délivrer en sortie un courant élévateur calculé (I_{BST_PRED}), le courant élévateur calculé (I_{BST_PRED}) étant un courant prévu d'être délivré en sortie par une inductance du convertisseur élévateur en fonction d'au moins le signal d'entrée (V_{IN}) et la tension de la source (V_{BAT}).

3. Circuit (3000, 8000) selon la revendication 2, dans lequel le modèle de courant de charge (4410) est configuré pour

recevoir en entrée V_L, une valeur représentative de la tension aux bornes de la charge (L),
recevoir en entrée I_L, une valeur représentative du courant aux bornes de la charge (L),
recevoir en entrée V_{IN}, une valeur représentative du signal d'entrée, et
délivrer en sortie le courant d'amplificateur calculé I_{OUT_PRED} comme étant

$$I_{OUT\_PRED} = f\left(V_{IN} * Y_L\right)$$

où Y_L est l'admittance de la charge (L) et où f est une fonction bijective.

4. Circuit (3000, 8000) selon l'une quelconque des revendications 2 ou 3, dans lequel le modèle de courant de charge (4410) comprend

un modèle de capacité de charge (4411) configuré pour délivrer en sortie une valeur de capacité calculée (C_{L_PRED}) de la charge (L) calculée à partir de V_L et I_L,
un modèle d'amplificateur (4412) configuré pour délivrer en sortie une tension de sortie prévue (V_{OUT_PRED}) de l'amplificateur calculée à partir de V_{IN},

un calculateur de courant (4413) configuré pour calculer le courant d'amplificateur calculé (I_{OUT_PRED}) sur la base de la valeur de capacité calculée (C_{L_PRED}) de la charge (L) et de la tension de sortie prévue (V_{OUT_PRED}) comme étant

$$I_{OUT\_PRED} = f \, (V_{OUT\_PRED} * Y_L)$$

où f est une fonction bijective.

5. Circuit (3000, 8000) selon la revendication 4, dans lequel le modèle de capacité de charge (4411) comprend un filtre à moyenne quadratique minimale.

6. Circuit (3000, 8000) selon l'une quelconque des revendications 3 à 5, dans lequel le modèle de courant de charge (4410) comprend un modèle d'une fonction de transfert tension vers courant de la charge (L).

7. Circuit (3000, 8000) selon l'une quelconque des revendications 2 à 6, dans lequel le modèle de courant élévateur (5420) est configuré pour recevoir en entrée V_{BAT}, une valeur représentative de la tension aux bornes de la source,

recevoir en entrée η, une valeur représentative d'un rendement du convertisseur élévateur,
recevoir en entrée I_{OUT_PRED}, une valeur représentative du courant d'amplificateur calculé,
recevoir en entrée V_{IN}, une valeur représentative du signal d'entrée,
délivrer en sortie le courant élévateur calculé I_{BST_PRED} comme étant

$$I_{BST\_PRED} = f \, [V_{OUT} * I_{OUT\_PRED} \, / \, (\eta * V_{BAT})]$$

où f est une fonction bijective.

8. Circuit (3000, 8000) selon l'une quelconque des revendications 2 à 7,

dans lequel le modèle dynamique (3400, 8400) comprend en outre une logique de détermination de coefficient (3430, 7430) configurée pour
recevoir en entrée le courant d'amplificateur calculé (I_{OUT_PRED}) et/ou le courant élévateur calculé (I_{BST_PRED}),
délivrer en sortie au moins un coefficient (R_{OFF}, X_{MULT}) pour la commande du filtre adaptatif (2300, 6300, 9300) sur la base de valeurs d'au moins l'un parmi le courant d'amplificateur calculé (I_{OUT_PRED}) et le courant élévateur calculé (I_{BST_PRED}).

9. Circuit (3000, 8000) selon la revendication 8, dans lequel

le filtre adaptatif (6300, 9300) comprend un filtre passe-bas variable (6310) ayant, comme entrée de commande, au moins un coefficient d'affaiblissement (R_{OFF}), et
la logique de détermination (3430, 7430) est configurée pour déterminer le coefficient d'affaiblissement (R_{OFF}) en fonction du courant élévateur calculé (I_{BST_PRED}) et/ou du courant de sortie calculé (I_{OUT_PRED}).

10. Circuit (8000) selon une quelconque revendication précédente, comprenant en outre un élément à retard (8500) connecté entre le signal d'entrée (V_{IN}) et le filtre adaptatif (2300, 6300, 9300).

11. Circuit (8000) selon une quelconque revendication précédente, comprenant en outre un second filtre adaptatif (8440) connecté entre le signal d'entrée (V_{IN}) et le modèle dynamique (3400, 8400),

dans lequel le second filtre adaptatif (8440) est configuré pour fournir sensiblement le même filtrage que le filtre adaptatif (2300, 6300, 9300),
dans lequel le second filtre adaptatif (8440) est configuré pour filtrer le signal d'entrée (V_{IN}) sur la base de la sortie du modèle dynamique (3400, 8400).

12. Circuit (3000, 8000) selon une quelconque revendication précédente,
dans lequel le filtre adaptatif (9300) comprend une pluralité de filtres passe-bas (9331, 9341) et de filtres passe-haut

(9332, 9342) pour le filtrage du signal d'entrée (V$_{IN}$) le long d'au moins deux branches, de préférence trois.

13. Circuit (8000) selon une quelconque revendication précédente,
dans lequel la charge capacitive (L) est un haut-parleur basé sur l'un ou plusieurs parmi un composant piézoélectrique ou un système micro-électro-mécanique, MEMS.

14. Dispositif comprenant un haut-parleur et un circuit (2000, 3000, 8000) selon une quelconque revendication précédente pour l'excitation du haut-parleur.

15. Unité informatique (10000) comprenant un processeur (10100) et une mémoire (10300), la mémoire comprenant des instructions qui, lors de leur exécution par le processeur, amènent le processeur à fonctionner comme le circuit selon l'une quelconque des revendications 1 à 13.

Fig. 1A   1000A

1100   1200A
                                        1210
                                                              L
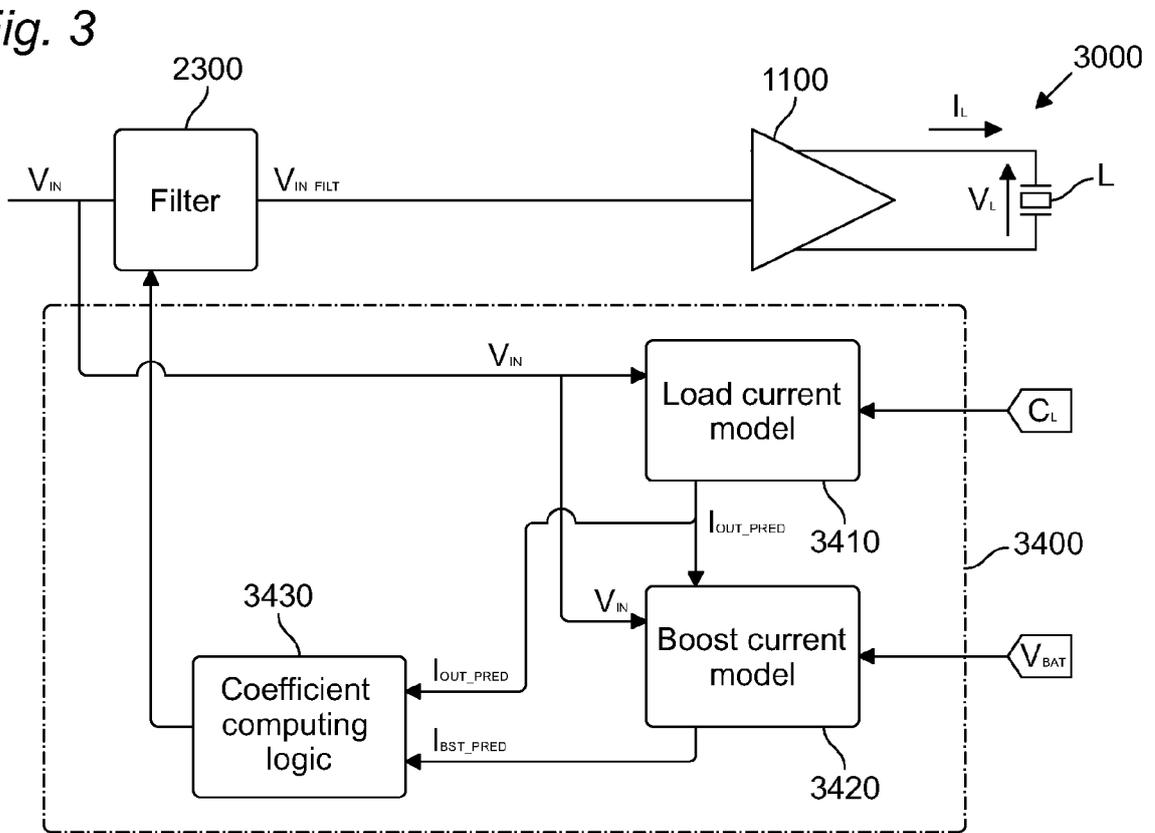
Fig. 1B   1000B

1200B   1100
                                                  L

Fig. 1C   1000   1000C

1300   1100
                                              L

1400
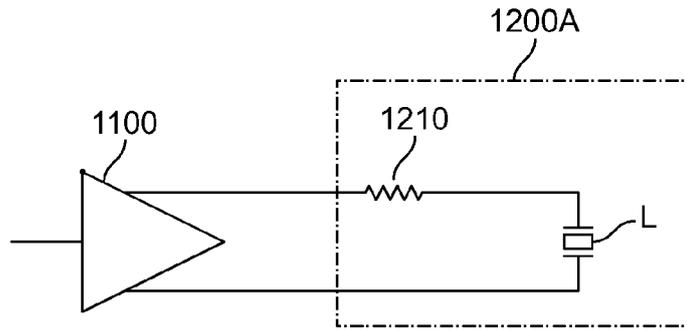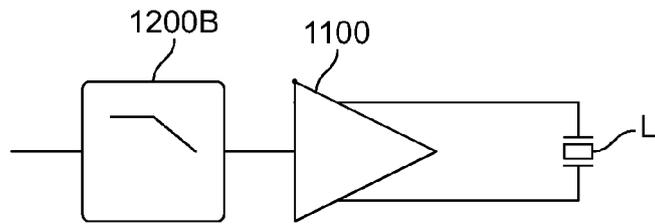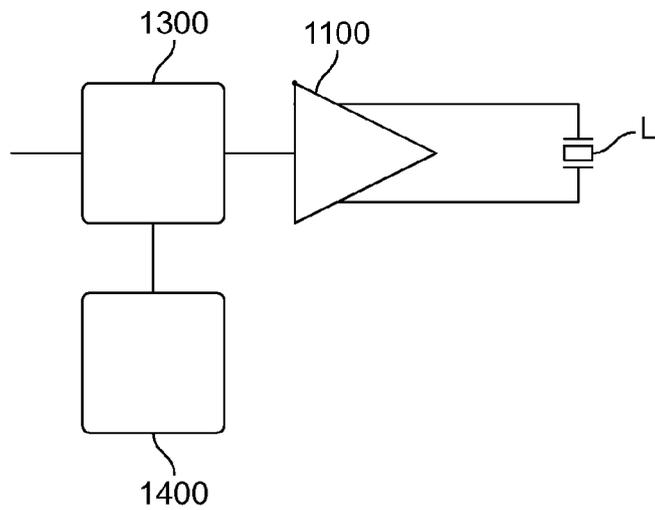
Fig. 2

Fig. 3

Fig. 3A

Fig. 4A

4410

Fig. 4B

Fig. 4C

4410

Fig. 5A

5420

Fig. 5B

5420
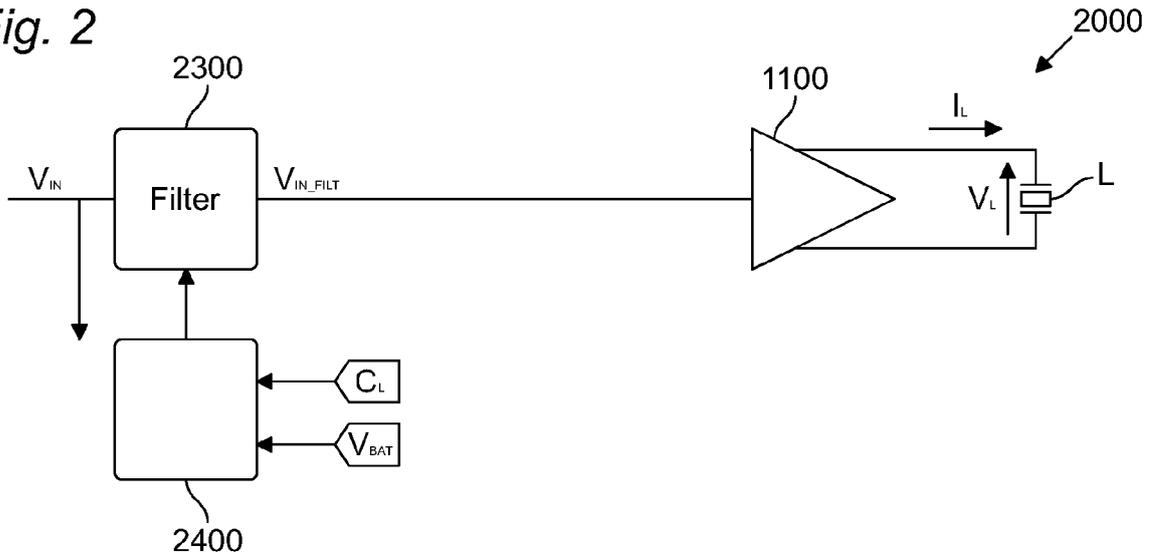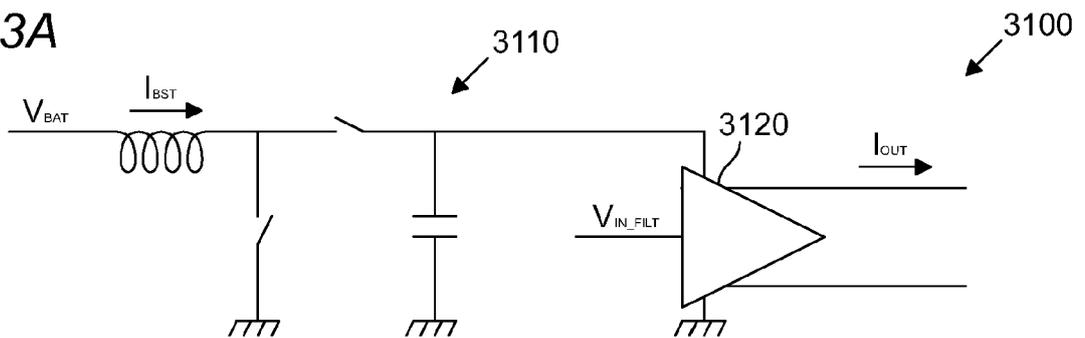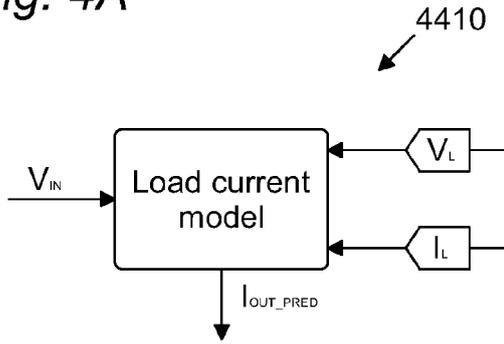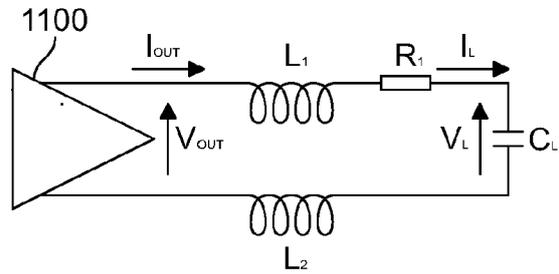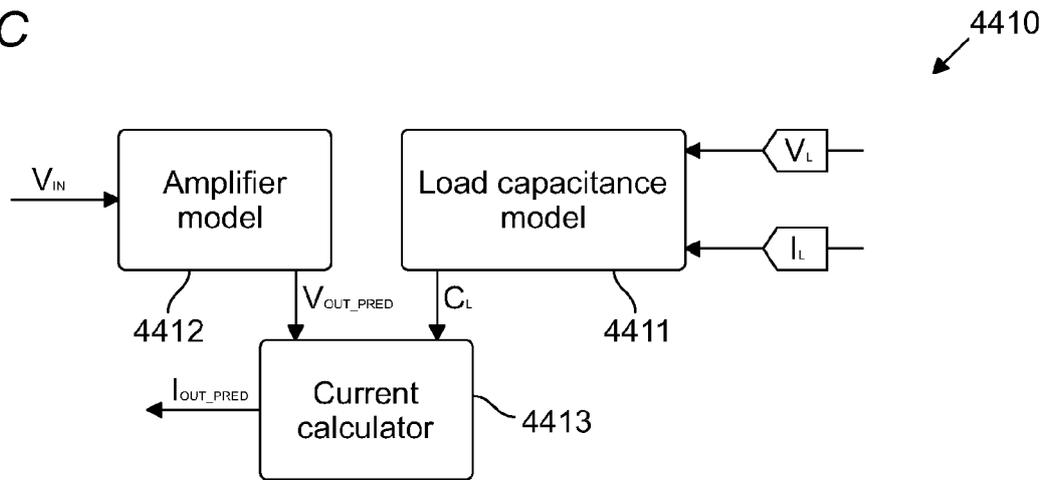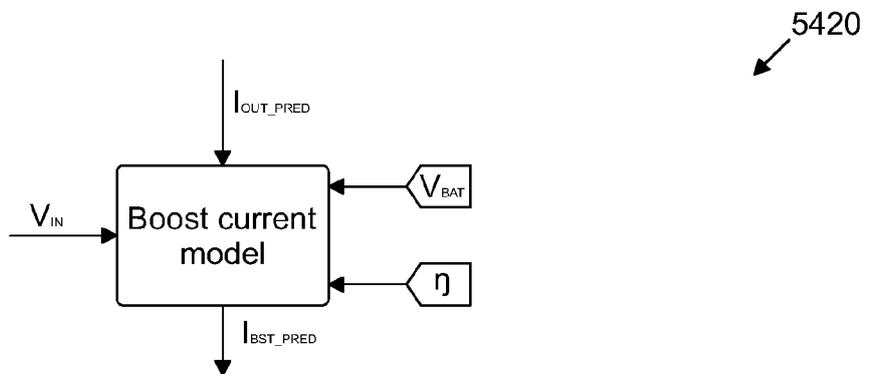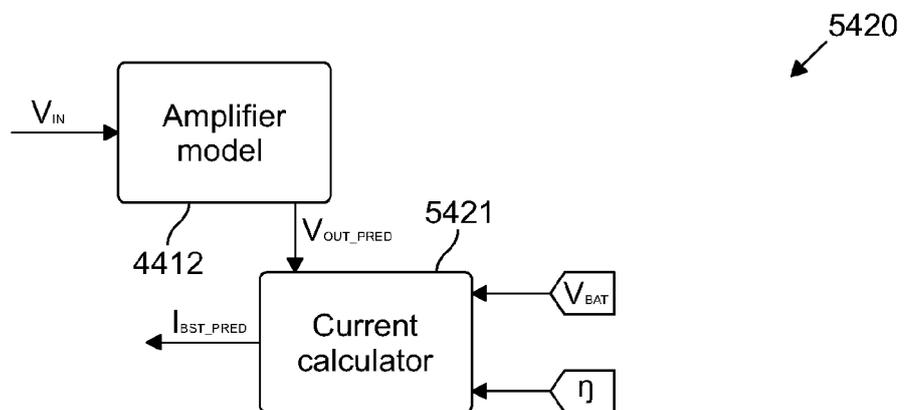
Fig. 6
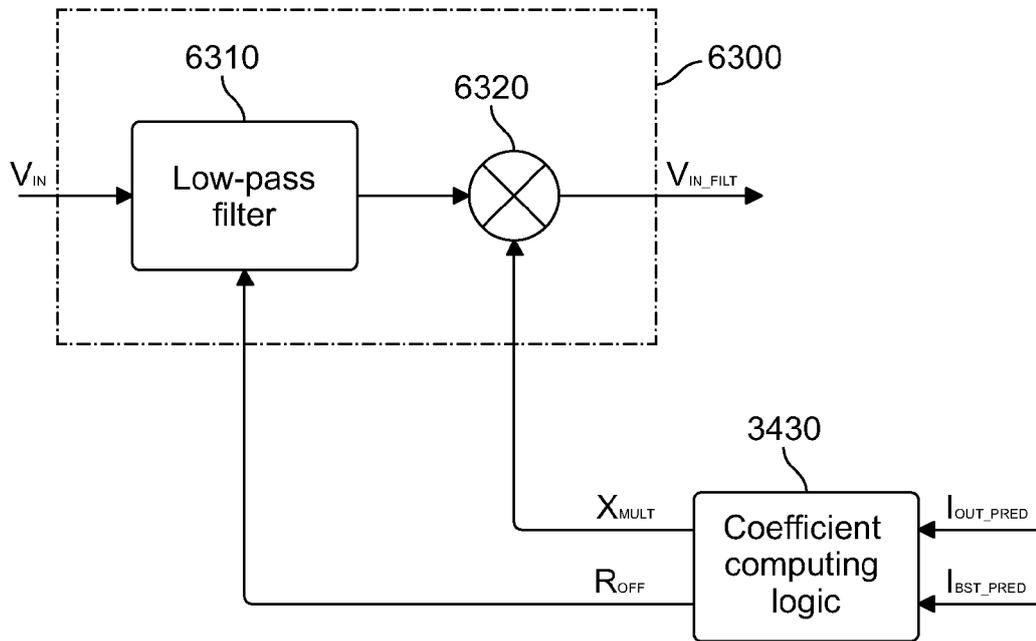
Fig. 7

Fig. 8

Fig. 9

Fig. 10   10000

```
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                    │        acquire inputs        │──── S101
                    └─────────────────────────────┘
                                   │
                                   ▼
                    ┌─────────────────────────────┐
                    │       compute outputs        │──── S102
                    └─────────────────────────────┘
                                   │
                                   ▼
                    ┌─────────────────────────────┐
                    │    configure adaptive filter │──── S103
                    └─────────────────────────────┘
                                   │
                                   ▼
                    ┌─────────────────────────────┐
                    │ filter input signal when driving load │──── S104
                    └─────────────────────────────┘
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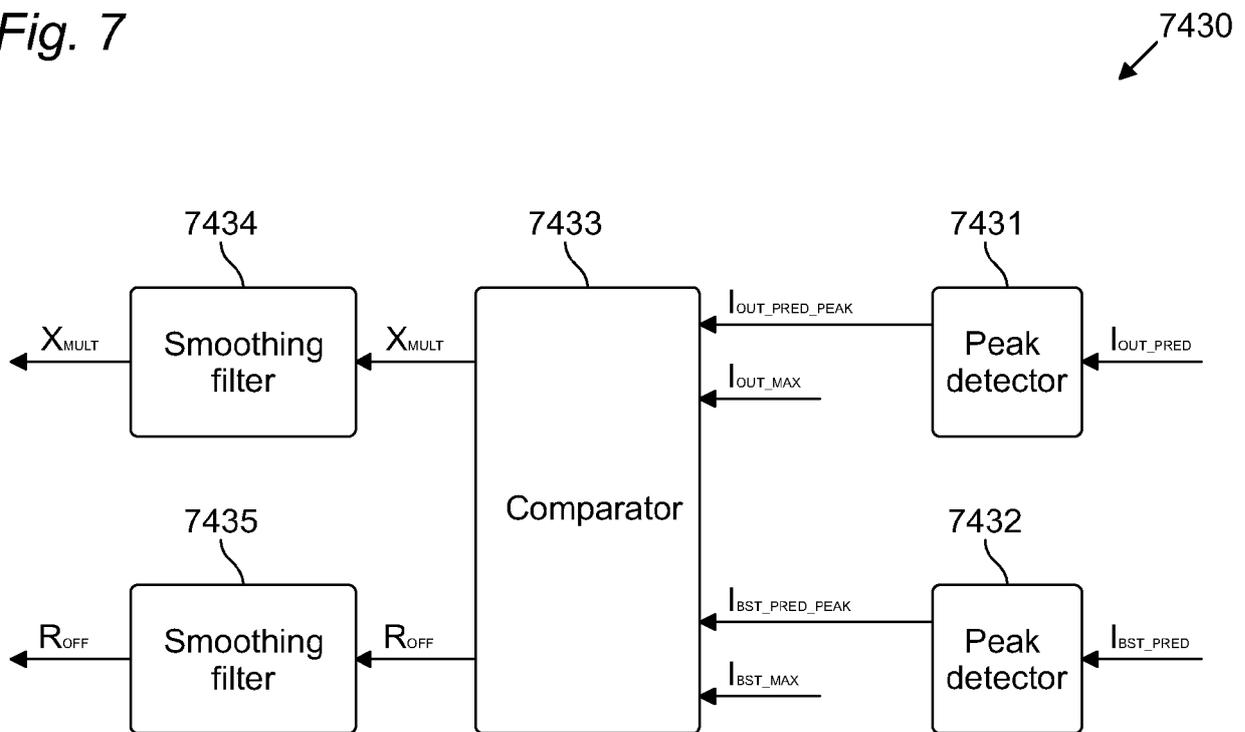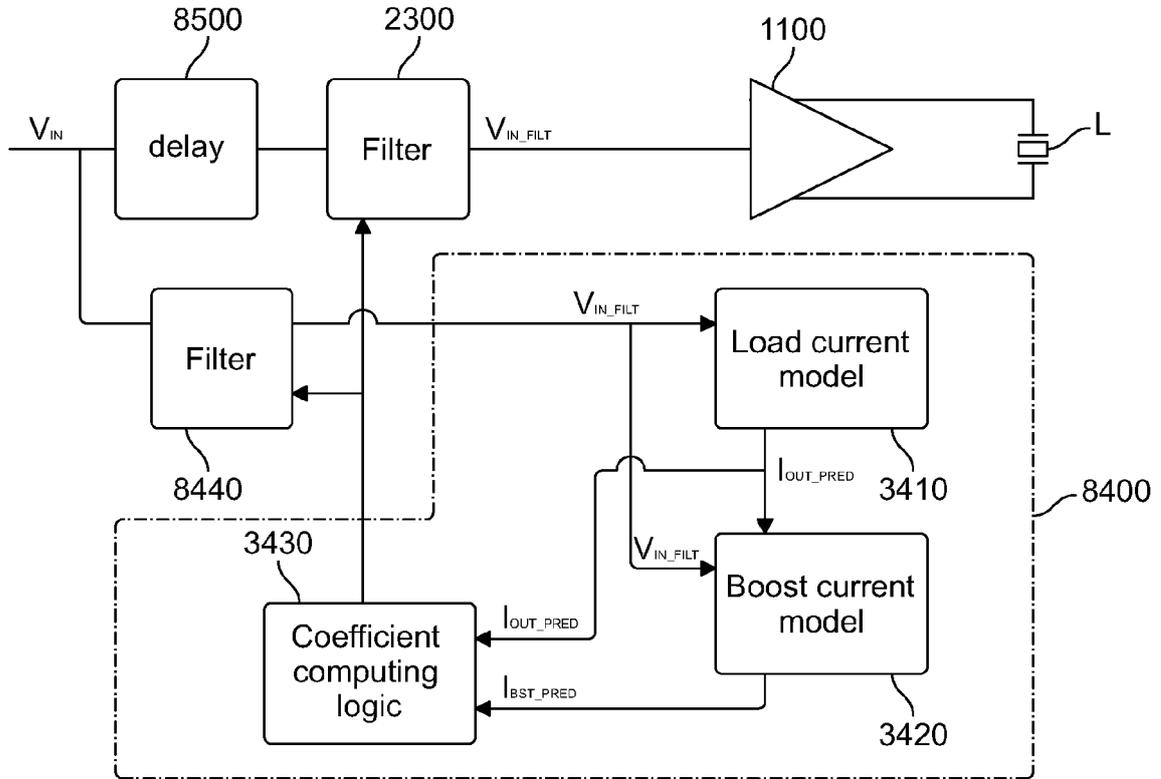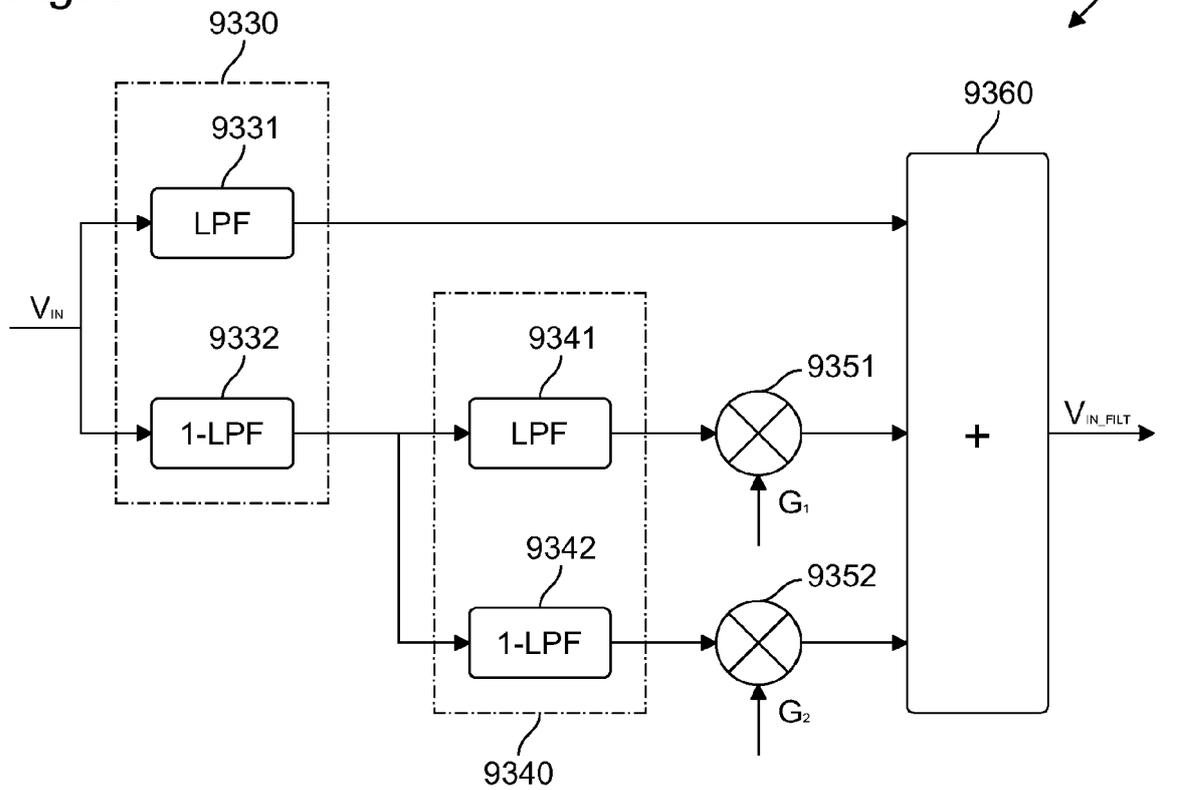
Fig. 11   11000
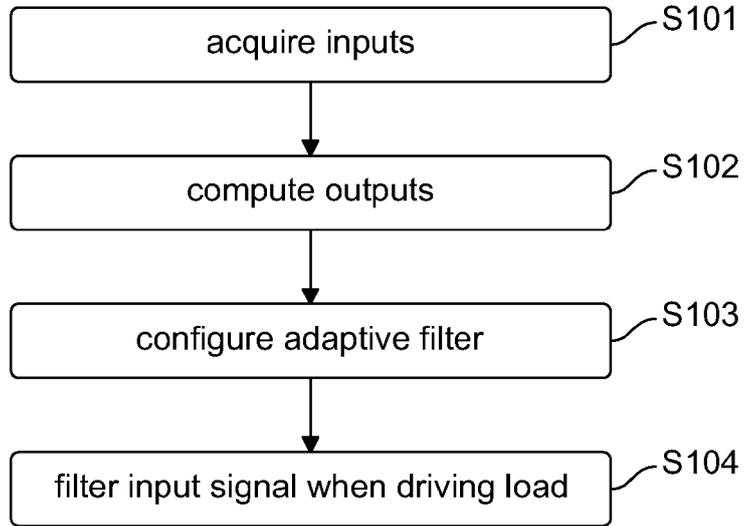
```
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      ┌───────┐          ┌───────┐
      │  CPU  │──────────│  I/O  │
      └───────┘          └───────┘
          │
      ┌───────┐
      │  MEM  │
      └───────┘
          │
        11300
```
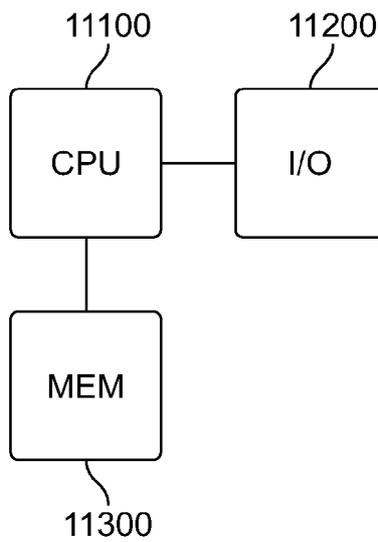
REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

• US 2019260333 A1 **[0014]**