Quintic vertices of spin 3, vector and scalar fields

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Abstract

As a result of special deformations of free gauge models of massless spin 3, massive vector and real scalar fields, quintic vertices within new approach Buchbinder and Lavrov \textsuperscript{32}; Buchbinder and Lavrov \textsuperscript{33}; Lavrov \textsuperscript{34} are constructed. They are described by local functionals which are invariant under original gauge transformations.

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1 Introduction

Beginning with famous papers of Fradkin and Vasiliev [1, 2] and Vasiliev [3, 4, 5] construction of interactions in the theory of high spin fields [6, 7] attracts an increasing interest due to numerous problems arising in this process (for recent discussions see [8, 9, 10]). At the present, there is strong opinion that the structure of cubic vertices are established very well [11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21] using different methods (deformation procedure in the BV formalism [22, 23, 24, 25], BRST construction [26], light-cone formalism [27]). Studies of quartic vertices led to open new problem of locality of interactions in this order [28, 29, 30, 31]. As to quintic vertices and vertices more of high orders (in our knowledge) there is no some explicit results.

Recently, a reformulation of the deformation procedure in the BV formalism has been proposed [32, 33, 34]. New method opens new possibilities in studies of interactions in the higher spin field theory thanks to an explicit and closed form of description of deformation procedure for gauge fields. From the point of view of the old approach based on the Noether procedure, this method seems as an explicit summation of the infinite Taylor series in deformation parameter leading to compact presentation of the deformed action and deformed gauge algebra. Analysis of simple gauge systems including massless spin 3, massive vector and real scalar fields within the new approach allowed us to study situations when in the process of deformation the original gauge symmetry does not deform [35, 36]. It was shown that cubic vertices invariant under original gauge transformations are forbidden while local gauge-invariant quartic vertices are explicitly found. In the present paper, we extend the results [35, 36] up to quintic vertices.

The paper is organized as follows. In section 2, quintic vertices for massless spin 3 and real scalar fields are constructed. In section 3, quartic vertices for massless spin 3, massive vector and real scalar fields are found. In section 4, discussions of obtained results are given.

The DeWitt’s condensed notations are used [37]. Arguments of any functional are enclosed in square brackets [], and arguments of any function are enclosed in parentheses, ( ).

2 Vertices $\sim \varphi \phi \phi \phi$

In this section, we are going to continue the research of possible interactions among massless spin 3 field, $\varphi^{\mu \nu \lambda} = \varphi^{\mu \nu \lambda} (x)$, and a real scalar field, $\phi = \phi (x)$, in flat Minkowski space of the dimension $d$ with the metric tensor $\eta_{\mu \nu}$ that was started in [35]. We begin with the initial action

$$S_0[\varphi, \phi] = \int dx \left[ \varphi^{\mu \nu \rho} \Box \varphi_{\mu \nu \rho} - 3 \eta_{\mu \nu} \eta^{\rho \sigma} \varphi^{\mu \nu \rho} \Box \varphi_{\rho \sigma \delta} - 3 \varphi^{\mu \rho \sigma} \partial_{\mu} \varphi_{\rho \sigma \delta} + 6 \eta_{\mu \nu} \varphi^{\mu \nu \delta} \partial^{\rho} \varphi_{\rho \sigma \delta} - \frac{3}{2} \varphi_{\mu \nu \lambda} \eta^{\mu \nu} \partial_{\alpha} \varphi^{\alpha \beta \gamma} \eta_{\beta \gamma} \right] + \int dx \frac{1}{2} \left[ \partial_{\mu} \phi \partial^{\mu} \phi - m^2 \phi^2 \right], \quad (1)$$

where the first five terms in the right hand side of (1) present the Fronsdal action for massless spin 3 field [6] and the last two terms correspond to the action of massive scalar field. The action (1) is invariant under the following gauge transformations,

$$\delta S_0[\varphi, \phi] = 0, \quad \delta \varphi^{\mu \nu \lambda} = \partial^{(\mu} \xi^{\nu \lambda)} \chi, \quad \delta \phi = 0, \quad (2)$$

where the gauge functions $\xi^{\mu \nu}$ obey the condition $\eta_{\mu \nu} \xi^{\mu \nu} = 0$.

According to general concept of [32, 33, 34], the interactions among fields are introduced with the help of anticanonical transformations in the BV formalism which act in the minimal antisymplectic space and transform a solution to the classical master-equation into another. To realize the deformation procedure for a given dynamical system with the gauge freedom, it is enough to operate special anticanonical transformations in the sector of original fields only. In the case under consideration, we choose the generating function of anticanonical transformations which acts in the sector of fields $\varphi^{\mu \nu \lambda}$ and depends on the scalar field, $h^{\mu \nu \lambda} = h^{\mu \nu \lambda} (\phi)$. Then,
the most general form of the generating function \( h^{\mu \nu \lambda} \) with three derivatives responsible for the generation of quintic vertices reads

\[
 h^{\mu \nu \lambda} = a_2 \frac{1}{\Box} \left[ c_1 \partial^\mu \partial^\nu \partial^\lambda \phi \phi^3 + c_2 \partial^{(\mu} \partial^\nu \partial^{\lambda)} \phi \phi^2 + c_3 \partial^\mu \phi \partial^{\nu} \phi \partial^{\lambda} \phi \phi + c_4 \eta^{(\mu \nu \lambda)} \Box \phi \phi^3 + 
 + c_5 \eta^{(\mu \nu \lambda)} \partial_\sigma \phi \partial^\sigma \phi \phi^2 + c_6 \eta^{(\mu \nu \lambda)} \phi \partial_\sigma \phi \partial^\sigma \phi \phi + c_7 \phi \eta^{(\mu \nu \lambda)} \phi \phi^2 \right],
\]

where \( a_2 \) is a coupling constant with \( \dim(a_2) = -(3d - 4)/2 \) and \( c_i, \ i = 1, 2, ..., 7 \) are arbitrary dimensionless constants.

The deformed action, \( \tilde{S}[\varphi, \phi] = S_0[\varphi + h, \phi] \), can be presented in the form

\[
 \tilde{S}[\varphi, \phi] = S_0[\varphi, \phi] + S_{3 \text{loc}}[\varphi, \phi] + (\text{non-local terms}),
\]

where \( S_{3 \text{loc}}[\varphi, \phi] \) is the local functional

\[
 S_{3 \text{loc}}[\varphi, \phi] = 2a_2 \int dx \varphi_{\mu \nu \lambda} \left[ c_1 \partial^\mu \partial^\nu \partial^\lambda \phi \phi^3 + c_2 \partial^{(\mu} \partial^\nu \partial^{\lambda)} \phi \phi^2 + c_3 \partial^\mu \phi \partial^{\nu} \phi \partial^{\lambda} \phi \phi - 
 - (c_1 + c_4(d + 1)) \eta^{(\mu \nu \lambda)} \Box \phi \phi^3 - (2c_2 + c_5(d + 1)) \eta^{(\mu \nu \lambda)} \partial_\sigma \phi \partial^\sigma \phi \phi^2 - 
 - (c_3 + c_6(d + 1)) \eta^{(\mu \nu \lambda)} \partial_\sigma \phi \partial^\sigma \phi \phi - (c_2 + c_7(d + 1)) \Box \phi \eta^{(\mu \nu \lambda)} \phi \phi^2 \right],
\]

describing interactions among the massless spin 3 and real scalar fields in the fifth order. By the same reasons explained in [35, 36], the gauge algebra does not deform under special anticanonical transformations \([3, 4] \), \( \delta \tilde{S}[\varphi, \phi] = 0 \). Due to the locality of original gauge transformations, the action \( S_{3 \text{loc}}[\varphi, \phi] \) should be also gauge-invariant, \( \delta S_{3 \text{loc}}[\varphi, \phi] = 0 \). Analysis of this requirement leads to the following conditions on the constants \( c_i, \ i = 1, ..., 7 \),

\[
 2c_2 = c_3 = 6c_1, \quad c_4 = -\frac{1}{2(d + 1)}c_1, \quad c_5 = c_6 = 2c_7 = -\frac{3}{(d + 1)}c_1.
\]

We state that the functional

\[
 S_{3 \text{loc}}[\varphi, \phi] = a_2 \int dx \varphi_{\mu \nu \lambda} \left[ \partial^{\mu} \partial^{\nu} \partial^{\lambda} \phi \phi^3 + 3 \partial^{(\mu} \partial^{\nu} \partial^{\lambda)} \phi \phi^2 + 6 \partial^{\mu} \phi \partial^{\nu} \phi \partial^{\lambda} \phi \phi - \frac{1}{2} \eta^{(\mu \nu \lambda)} \Box \phi \phi^3 
 - 3 \eta^{(\mu \nu \lambda)} \partial_\sigma \phi \partial^\sigma \phi \phi^2 - 3 \eta^{(\mu \nu \lambda)} \partial_\sigma \phi \partial^\sigma \phi \phi - \frac{5}{2} \Box \phi \eta^{(\mu \nu \lambda)} \phi \phi^2 \right],
\]

is gauge-invariant under original gauge transformations \([3, 4] \),

\[
 \delta S_{3 \text{loc}}[\varphi, \phi] = 0.
\]

and describes quintic vertices. The action \( S_{3 \text{loc}}[\varphi, \phi] \) is local and presents the exact form of quintic vertices which cannot be constructed using the standard Noether procedure adopted in the theory of higher spin fields (for detailed description of relations between the standard Noether procedure and new method see [35]).

### 3 Vertices \( \sim \varphi A \phi \phi \phi \)

Here, we want to elaborate interactions among massless spin 3, massive vector and real scalar fields in the framework of deformation procedure [32, 33, 34] beginning with the free initial action,

\[
 S_0[\varphi, A, \phi] = S_0[\varphi, \phi] + S_0[A],
\]
where the action $S_0[\varphi, \phi]$ was defined in (1) and

$$S_0[A] = -\int dx \left( \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m^2_0 A_\mu A^\mu \right), \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

is the action of massive vector field. The action (9) is invariant under the gauge transformations

$$\delta \varphi^{\mu \nu \lambda} = \partial^{(\mu} \xi^{\nu \lambda)}, \quad \eta_{\mu \nu} \xi^{\nu \lambda} = 0, \quad \delta A_\mu = 0, \quad \delta \phi = 0.$$  (11)

The cubic ($\sim \varphi A \phi$) and quartic ($\sim \varphi A \phi \phi \phi$) vertices for the initial gauge model (9) have been studied in [36]. It was shown that the local cubic vertices invariant under original gauge transformations are forbidden while the local quartic vertices are constructed in the form of explicit functional which is exactly invariant under the initial gauge symmetry.

Consider now quintic vertices ($\sim \varphi A \phi \phi \phi \phi$) in the model under consideration. It is enough to chose the generating function of anticanonical transformations in the form

$$h^{\mu \nu \lambda} = a_2 \frac{1}{\Box} K^{\mu \nu \lambda},$$  (12)

where $K^{\mu \nu \lambda} = K^{\mu \nu \lambda}(A, \phi)$ is the local functional

$$K^{\mu \nu \lambda} = c_1 \partial^{(\mu} \partial^{\nu} A^{\lambda)} \phi^3 + c_2 (\partial^{(\mu} A^{\nu)} \partial^{(\lambda)} \phi \phi^2 + c_3 A^{(\mu} \partial^{\nu} \partial^{(\lambda)} \phi \phi^2 + c_4 A^{(\mu} \partial^{\nu} \phi \partial^{(\lambda)} \phi \phi +$$

$$+ c_5 \eta^{(\mu \nu \Box A^{(\lambda)} \phi^3 + c_6 \eta^{(\mu \nu \partial A^{(\lambda)} \partial \phi^2 + c_7 \Box \phi \eta^{(\mu \nu A^{(\lambda)} \partial \phi + \partial \phi} +$$

$$+ c_8 \eta^{(\mu \nu \partial \phi \partial A^{(\lambda)} \phi^2 + c_9 \eta^{(\mu \nu \partial \phi \partial A^{(\lambda)} \phi^2 + c_{10} \eta^{(\mu \nu \partial \phi \partial A^{(\lambda)} \partial \phi \phi^2 + c_{11} \eta^{(\mu \nu \partial \phi \partial A^{(\lambda)} \partial \phi \phi^2 +}$$

$$+ c_{12} \eta^{(\mu \nu \Box \partial \phi \partial A^{(\lambda)} \phi^2 + c_{13} \eta^{(\mu \nu \Box \partial \phi \partial A^{(\lambda)} \phi^2 + c_{14} \eta^{(\mu \nu \Box \partial \phi \partial A^{(\lambda)} \phi^2 + c_{15} \eta^{(\mu \nu \Box \partial \phi \partial A^{(\lambda)} \phi^2 + c_{16} \eta^{(\mu \nu \Box \partial \phi \partial A^{(\lambda)} \phi^2 + c_{17} \eta^{(\mu \nu \Box \partial \phi \partial A^{(\lambda)} \phi^2 + c_{18} \eta^{(\mu \nu \Box \partial \phi \partial A^{(\lambda)} \phi^2 + c_{19} \eta^{(\mu \nu \Box \partial \phi \partial A^{(\lambda)} \phi^2 +}$$

$$a_2 \text{ a coupling constant with } \text{dim}(a_2) = -(3d - 6)/2 \text{ and } c_i, \ i = 1, 2, \ldots, 13 \text{ are dimensionless constants. Modification of local part of the deformed theory in terms of } K^{\mu \nu \lambda} \text{ is described by the functional}$$

$$S_{3 \text{loc}}[\varphi, A, \phi] = 2a_2 \int dx \varphi^{\mu \nu \lambda}[K^{\mu \nu \lambda} - \eta^{(\mu \nu K^{(\lambda)} \mu \sigma \eta_{\nu \sigma}].$$  (14)

Note that the gauge algebra does not deform under anticanonical transformations generated by the function $h^{\mu \nu \lambda}$ (12), (13). It leads to the requirement for the functional (14) to be invariant under original gauge transformations (11),

$$\delta S_{3 \text{loc}}[\varphi, A, \phi] = 0.$$  (15)

Analysis of this equation gives the following conditions on constants $c_i, \ i = 1, 2, \ldots, 13$

$$c_2 = 2c_3 = c_4 = 6c_1, \ c_5 = c_6 = c_7 = c_8 = 0, \ c_9 = 3c_{10} = 3c_{11} = 3c_{12} = 6c_{13} = -\frac{3}{2(d+1)}c_1.$$  (16)

As a result, the local functional

$$S_{3 \text{loc}}[\varphi, A, \phi] = 2a_2 \int dx \varphi^{\mu \nu \lambda}[\partial^{(\mu} \partial^{\nu} A^{\lambda)} \phi^3 + 6\partial^{(\mu} A^{\nu)} \partial^{(\lambda)} \phi \phi^2 + 3A^{(\mu} \partial^{\nu} \partial^{(\lambda)} \phi \phi^2 +$$

$$+ 6A^{(\mu} \partial^{\nu} \phi \partial^{(\lambda)} \phi - \eta^{(\mu \nu \Box A^{(\lambda)} \phi^3 + 6\eta^{(\mu \nu \partial A^{(\lambda)} \partial \phi^2} - 3\Box \phi \eta^{(\mu \nu A^{(\lambda)}} \phi^2 -$$

$$-6\eta^{(\mu \nu A^{(\lambda)}} \partial \phi \partial \phi - \frac{1}{2} \eta^{(\mu \nu \partial A^{(\lambda)}} \partial \phi \partial \phi = -\frac{1}{2} \eta^{(\mu \nu \partial A^{(\lambda)}} \partial \phi A^{\sigma} \phi^3 - \frac{11}{2} \eta^{(\mu \nu \partial A^{(\lambda)}} \partial \phi A^{\sigma} \phi^2 -$$

$$- \frac{11}{2} \eta^{(\mu \nu \partial A^{(\lambda)}} A^{\sigma} \partial \phi \phi^2 - \frac{5}{2} \eta^{(\mu \nu \partial A^{(\lambda)}} \partial \phi A^{\sigma} \phi^2 - \frac{47}{4} \eta^{(\mu \nu \partial A^{(\lambda)}} A^{\sigma} \partial \phi \phi \right]$$  (17)

describes quintic vertices. These vertices are invariant under original gauge transformations and may be considered as the first explicit construction of interactions of the fifth order in the theory of higher spin fields.
4 Discussion

In the present paper, quintic vertices describing interactions among massless spin 3 field and massive vector and real scalar fields have been constructed. The construction was based on the new approach to the deformation procedure \[32, 33, 34\].

Main advantage of the new approach is related with possibility to present the deformation of a given dynamical system with gauge freedom in a closed and explicit form using a generating function of anticanonical transformations of the BV formalism. Final results of the deformation are formulated in a simple enough way. Namely, if \( S_0[A] \) is an initial action of fields \( A^i \) invariant under gauge transformations \( \delta A^i = R^i_\alpha (A) \xi^\alpha \) then the deformed action \( \tilde{S}[A] \) is constructed by the rule \( \tilde{S}[A] = S_0[A + h(A)] \), where \( h^i(A) \) is the generating function of anticanonical transformations which act non-trivially in the space of initial fields \( A^i \) only. The deformed action is invariant under deformed gauge transformations \( \tilde{\delta} A^i = (M^{-1}(A))^i_j R^j_\alpha (A + h(A)) \xi^\alpha \), \( \tilde{\delta} \tilde{S}[A] = 0 \), where \( (M^{-1}(A))^i_j \) is the matrix inverse to \( (M(A))^i_j = \delta^i_j + h^i(A) \partial A^j \).

The vertices considered in this paper were constructed using very special anticanonical transformations that do not deform the gauge algebra. In turn, this made it possible to quite simply single out the local part of the deformed action and analyze the conditions for its invariance. Interest to results obtained in the paper may be connected at least with two reasons. Firstly, in our knowledge, quintic vertices did not construct for any models of the theory of higher spin fields. Secondly, in connection with the problem of locality in the high spin theory \[8, 9, 10\], examples \(7, 17\) give local gauge-invariant vertices, which allow to assume the existence of local vertices in higher orders of the perturbation theory.

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